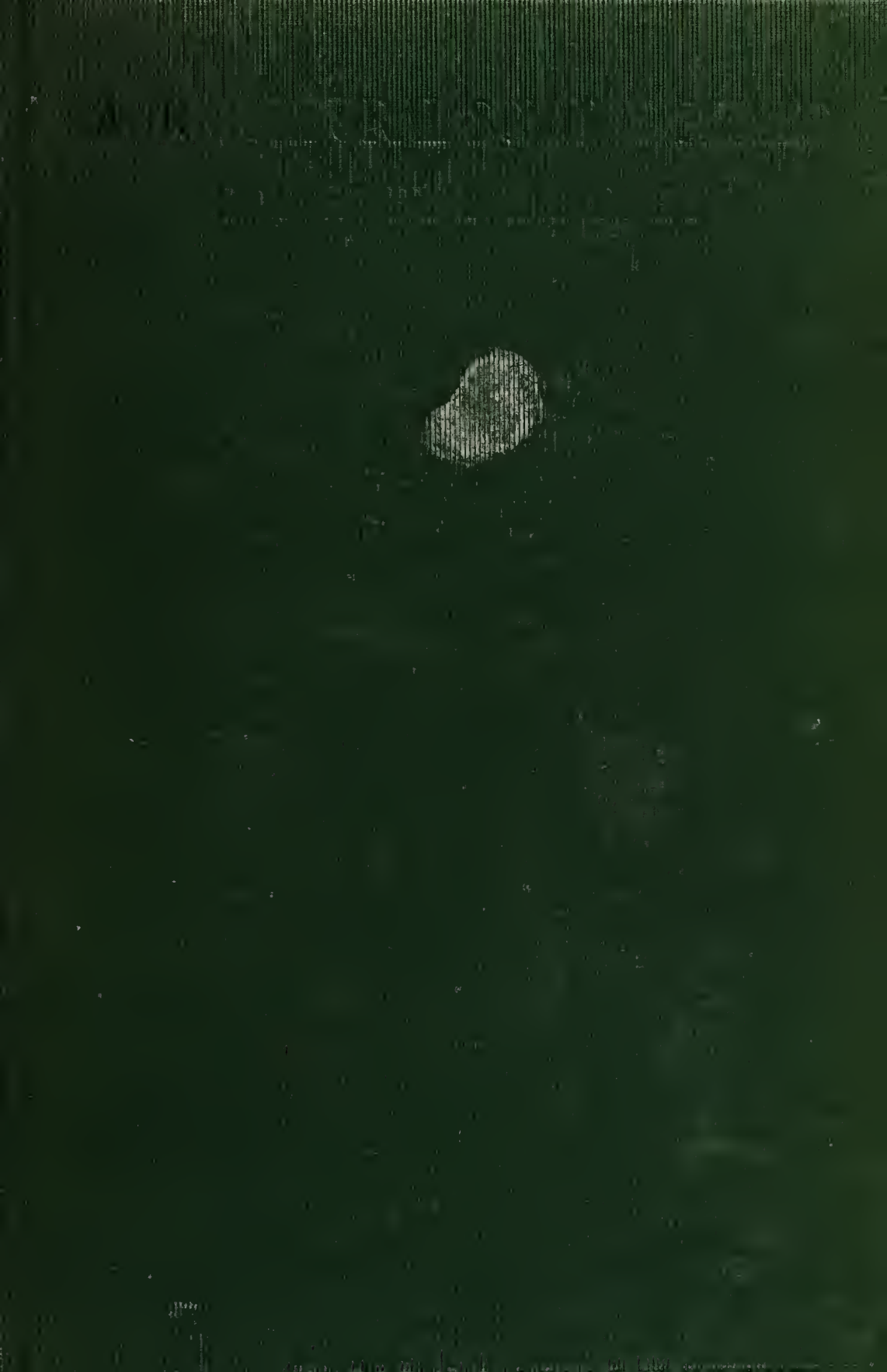

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THE NATURE AND PROPERTIES OF SOILS

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THE NATURE AND PROPERTIES OF SOILS

A COLLEGE TEXT OF EDAPHOLOGY

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AGRICULTURAL SCIENCE SERIES

UNDER THE EDITORSHIP OF

L. H. BAILEY

THE NATURE AND PROPERTIES OF SOILS,

by T. Lyttleton Lyon and Harry O. Buckman

NATURE AND PROPERTIES OF SOILS

CHAPTER I

SOME CONCEPTIONS OF THE SOIL AND ITS RELATIONS TO PLANTS

Due to the action of climatic agencies the outer solid portions of the earth readily pass into a loose and disintegrated condition. This layer, although superficial and insignificant in comparison to the bulk of the earth, has performed and is still performing a marvelous function. Life on the earth has been slowly but steadily developing and changing until we see about us the forms that characterize our age. This evolution has depended to no small degree on this superficial layer of decomposed rock with its admixture of decaying organic matter which together form the soil. In this medium many and varied organisms have lived and from it have drawn, wholly or in part, their sustenance, leaving as a recompense a contribution of organic debris, which in its turn has given rise to reactions of almost unbelievable complexity.

Like the life which it has sustained and nourished, the soil has been changing and evolving. The soil of today is not the soil of yesterday nor will it be the soil of tomorrow. It is never still. It is continually seeking a mechanical and chemical adjustment with the forces which surround it or

are active within its precincts. Such an equilibrium it never attains and thus the evolution goes on and on. It is this continual change and this endless response to environment that makes the soil useful to plants. The disintegrating rock and the decaying organic additions are thus converted into a mechanical support for plants, while at the same time they are forced to liberate the nutrients essential to plant growth.

In the light of its origin and function the soil may be defined as a mixture of broken and weathered fragments of rock and decaying organic matter, which covers the earth in a thin layer and supplies mechanical support and in part sustenance to plants.

This debris of rock and plant residue, teeming with its microscopic life and ever restless in its endless efforts at equilibrium, is the arable soil from which man must obtain his bread. As the light of investigation is thrown on it, new changes, new functions and new and unsuspected relationships are brought to view until the story of the soil may be retold with a clearer insight into those processes that render it useful to man.

1. Composition of the soil.—The soil as defined is composed of two general classes of material, mineral and organic. The former in most cases makes up from 90 to 99 per cent. by weight of the dry substance of a soil, the organic matter, except in the case of peat and muck, being in relatively smaller amounts. In spite of the low proportion of organic matter its presence is vital, not only because of its influence physically but because of the nutrients, especially nitrogen, that it carries. The mineral portion of a soil functions as a frame-work and as a source of certain chemical elements, which are necessary to proper crop growth and development.

It must be realized at the very outset that the two main constituents in a normal soil exist in very intimate relation-

ship, reactions occurring not only within each group but between the groups as well. Unless such interactions take place it is unlikely that the mixture will ever be in a condition either chemically, physically or biologically to sustain plant growth. These reactions, although very complex, take place with surprising ease and rapidity. As a consequence the study of this complex, heterogeneous and highly dynamic mass that we call the soil is often beset with difficulties that completely baffle our present facilities for its study.

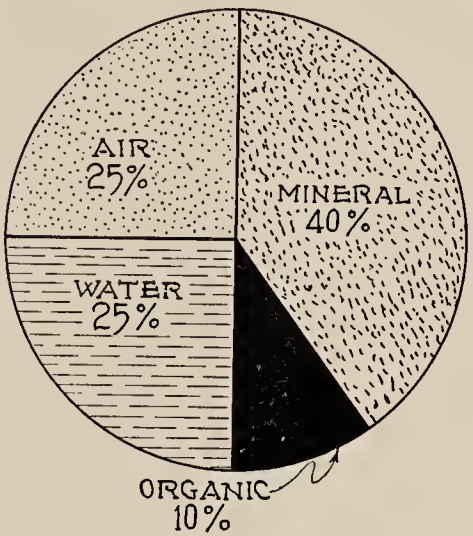


FIG. 1. — Volume composition of a loam soil when in good condition for plant growth. The air and water in a soil are variable and their proportion determines to a considerable degree the productivity.

2. Soil-forming rocks.[1] —In any study of soil origin or composition, however cursory, the geological phases of the problem immediately force attention. This is due to the bearing that certain geological phenomena have on soil conditions and crop growth. In the soil we find that the inorganic materials have originated from the common rocks. The best known country rocks are of course involved because they present the greatest outcrop surface and of necessity must contribute most to the mineral fabrication of the soil. They are classified under three heads—igneous, sedimentary and metamorphic. The most important types from the standpoint of soil formation are the following:

[1] For excellent non-technical discussions of rocks and minerals:— Pirsson, L. V., *Rocks and Rock Mincrals;* New York, 1915. Merrill, G. P., *Rocks, Rock Weathering and Soils;* New York, 1906.

Igneous	Sedimentary	Metamorphic
Granite	Limestone	Marble
Syenite	Dolomite	Schist
Diorite	Shale	Slate
Gabbro	Sandstone	Quartzite
Basalt	Conglomerate	Gneiss

The mineralogical complexity of rocks has an important bearing on the question of soil formation and soil composition. The fragments of any soil are, for the most part, distinguishable as separate minerals rather than as mineral aggregates. For example, a soil from a granite would be characterized by separate grains of quartz, orthoclase, microcline and perhaps mica rather than by fragments of the original granite itself. Again, it is the composition of the easily decomposable minerals rather than the composition of the bulk rock that determines what simplifications shall occur, what new substances shall arise in the soil and what elements shall be liberated for plant use.

3. Soil minerals.—Although hundreds of minerals have been identified, comparatively few are common or important[1] in rock formation. As a consequence, the list of important minerals found in soils will be correspondingly curtailed, although enough are always present, especially in the finer portions, to make the soil very complex mineralogically. The minerals as to origin may be divided into two groups: (1) those that persist from the original rock and (2) those that are produced by the decomposition of the original minerals, during soil formation. For example, the quartz grains

[1] The following table indicates the approximate proportions of the common minerals in the earth's crush to a depth of ten miles:

Feldspars	57.8%	Clay	1.0%
Amphibole and Pyroxene	16.0	Carbonates	.5
Quartz	12.7	Limonite	.2
Mica	3.6	All others	8.2

Recalculated from Clarke, F. W., *Data of Geochemistry;* U. S. Geol. Survey, Bul. 695, pp. 32-33. 1920.

of soil almost always come directly from the original rock as do particles of orthoclase, biotite, and apatite. Hematite, the kaolinite group and the chlorite and epidote groups generally originate in soils through weathering. The following list of minerals is by no means complete, yet it includes the more important forms from the soil and plant standpoint.

A LIST OF THE MOST IMPORTANT SOIL MINERALS.[1]

(The elements in bold type are those necessary for plant nutrition.)

1. Quartz	SiO_2
2. Orthoclase and Microcline feldspar	**K**$AlSi_3O_8$
3. Muscovite mica	**K**$H_2Al_3Si_3O_{12}$
4. Biotite mica	**K**H**Mg****Fe**$Al_2Si_3O_{12}$
5. Plagioclase feldspar	**Ca** and Na aluminum silicates
6. Calcite and Dolomite	**Ca**CO_3 and (**Ca, Mg**) CO_3
7. Hornblende and Augite	**Ca, Mg, Fe** aluminum silicates
8. Olivine	(**Mg, Fe**)$_2SiO_4$
9. Apatite	**Ca**$_5$ (**P**O_4)$_3$(Cl, F)
10. Kaolinite group	Typified by kaolinite. $H_4Al_2Si_2O_9$
11. Serpentine and Talc	Hydrated **Mg** silicates
12. Chlorite group	Hydrated **Mg, Fe** aluminum silicates
13. Epidote group	Hydrated **Ca, Fe** aluminum silicates
14. Hematite	**Fe**$_2O_3$
15. Limonite group	Typified by limonite 2 **Fe**$_2O_3$. 3 H_2O

[1] Below are some of the most important mineralogical investigations of soil: McCaughey, W. G., and Williams, H. F., *The Microscopic Determination of Soil-Forming Minerals;* U. S. Dept. Agr., Bur. Soils, Bul. 91. 1913. Plummer, J. K., *Petrography of Some North Carolina Soils and Its Relationship to their Fertilizer Requirements,* Jour. Agr. Res., Vol. V, No. 13, pp. 569-581. 1915. Robinson, W. O., *The Inorganic Composition of Some Important American Soils;* U. S. Dept. Agr., Bul. 122. Aug., 1914.

4. Importance of soil minerals.—Quartz is found in almost all soils, making up often from 80 to 90 per cent. of the composition, although a range from 40 to 70 per cent. is more common. Its universal presence is due to its hardness and insolubility. Quartz is a make-weight material, however, as it probably contributes but little to plant nutrition. In the form of sand, quartz has a great influence on the friability of soil, improving and maintaining the physical condition to a marked degree.

Orthoclase, microcline, muscovite and, to a lesser degree, biotite are important because of their potash content.[1] They decompose, often rather readily, into kaolinite and similar products, thus liberating potassium in soluble form. The plagioclase feldspars also give rise to kaolinite. They carry, however, sodium and calcium. The latter element[2] plays an important rôle in soil both as a nutrient and as an amendment. When not sufficiently active it must be applied in some form. Calcite and dolomite also carry calcium. Hornblende and augite bear calcium as well as magnesium and iron. Olivine is a magnesium and iron silicate. The oxidation of the iron of the above minerals gives rise to hematite, so common as a red coloring matter of soil.

Practically all of the phosphorus of the soil, either organic or inorganic, has its origin in apatite, yet this mineral occurs but sparingly either in rock or soil. It makes up but 6 per cent. of igneous rocks. This accounts for the small percentage of phosphoric acid in most soils and explains why it is often added in fertilizers.[3]

[1] Plummer, J. K., *Availability of Potash in Some Common Soil-forming Minerals,* Jour. Agr. Res., Vol. XIV, No. 8, pp. 297-315. Aug., 1918. de Turk, E., *Potassium-bearing Minerals as a Source of Potassium for Plant Growth;* Soil Sci., Vol. 8, No. 4, pp. 269-301. 1919.

[2] Shorey, E. C. *et al., Calcium Compounds in Soils;* Jour. Agr. Res., Vol. VII, No. 3, pp. 57-77. Jan., 1917.

[3] Fry, W. H., *Condition of Phosphoric Acid Insoluble in Hydrochloric Acid;* Jour. Ind. and Eng. Chem., Vol. V, No. 8, pp. 664-665. 1913.

The members of the kaolinite group are decomposition products resulting from the decay of the feldspars and similar minerals. While kaolinite itself shows no nutrients in its formula, it often carries considerable calcium, potassium, magnesium and phosphorus by absorption. Moreover, its close association with other decomposition products such as serpentine, talc, chlorite and epidote tends to accentuate its importance in plant nutrition. The plasticity and cohesion imparted to a soil by the presence of the kaolinite group and its associated minerals are of great practical importance as is also the capacity to hold, either physically or chemically, the bases already mentioned.

Hematite and limonite are simple iron compounds and usually occur in the soil as a result of the decomposition of certain iron-bearing minerals such as biotite, hornblende and augite. These iron compounds impart the red and yellow colors so characteristic of certain southern soils. Most of the soluble iron of the soil has its source in these minerals. Hematite and limonite are produced by the same general processes as are the kaolinite group and are found in very intimate contact with the serpentine, epidote, chlorite and kaolinite.

5. Soil organic matter.—One of the essential differences between a normal fertile soil and a mass of rock fragments lies in the organic content of the former. The organic matter practically all comes from plants and animals that have invested the surface of the soil and the soil material. Through the agency of bacteria and other organisms with which the soil is liberally supplied, this organic tissue quickly loses its original form, and becomes the dark incoherent material so noticeable in fertile soils. The decay is not one of immediate simplification, as might be supposed. The split-off compounds react not only with materials of a similar origin but also with the decomposing mineral fragments. This tendency provides the intimate relationship between the organic and inorganic constituents of the soil already emphasized as an ex-

ceedingly desirable condition. Incidentally the soil is rendered thereby very much more difficult to study, especially chemically.

The incorporation of organic matter in any soil, either by natural or artificial means, tends, if the proper decay occurs, to make the soil more friable. The water capacity is markedly increased and the vigor of the bacterial and chemical activities stimulated to a marked degree. As these two latter actions progress, some of the organic matter passes into simple combinations, allowing certain elements to become available to crops. Nitrogen, which is held in the soil largely in organic combination, emerges in the form of ammonia, nitrites and nitrates. It is from a salt of nitric acid that most plants absorb their nitrogen. Small amounts of sulfur, phosphorus, potassium and calcium are liberated from the tissue as decay proceeds. The largest product of organic decay, however, is carbon dioxide (CO_2), which in the soil becomes important as a solvent for minerals, thus hastening the decomposition processes.

6. Factors for plant growth.—The growth and development of a plant depends on two sets of factors, the internal and external. The latter may be classified as follows: (1) mechanical support, (2) heat, (3) light, (4) oxygen, (5) water, and (6) nutrients.[1] With the exception of light, the soil supplies, either wholly or in part, all of these conditions. Mechanical support is a function entirely of the soil. The comparatively loose and friable condition presented by most soils allows ample foothold to the ramifying roots.

Air and water are easily supplied because of the open condition of the soil, and its large pore spaces. Temperature depends almost wholly on climatic relationships. The water

[1] Nutrients are materials from which food may be elaborated once they have been absorbed by plants. The energy for this synthetic process comes from the sun. A food is any substance from which the plant may obtain energy for its normal processes. A large proportion of the materials absorbed by plants are nutrients.

of the soil acts as a plant nutrient in itself and functions also as a solvent for other materials. By its circulation it not only promotes solution but it continually brings nutrient elements in contact with the absorbing surfaces of the roots. The two prime functions of the soil are thus realized through the factors discussed above—mechanical support and a sufficient supply of certain nutrient elements under favorable conditions.

7. Nutrient elements.[1]—Although the physical condition of the soil exerts a far-reaching influence on plant growth, the relationships involved are more readily understood than those which have to do with plant nutrition. Moreover, the solubility of the necessary nutrients is very closely related to the complex processes of soil formation. Ten elements[2] are usually considered as necessary for plant growth. If one is lacking, normal development will not occur. They may be classified as follows:

From air or water	*From the soil*	
Carbon	Nitrogen	Calcium
Oxygen	Phosphorus	Magnesium
Hydrogen	Potassium	Sulfur
Nitrogen		Iron

Plants obtain most of their carbon and oxygen directly from the air by photosynthesis and respiration. The hydrogen comes, at least partially, from water. All of the other elements, except a small amount of nitrogen utilized directly from the air by certain plants, are obtained from the soil. It must not be inferred, however, that the bulk of the plant

[1] For an excellent discussion of the functions of plant nutrients, see Russell, E. J., *Soil Conditions and Plant Growth,* Chap. II, pp. 30-46; New York. 1915.

[2] It may be possible that manganese and silicon and possibly chlorine and fluorine function as nutrients. They as well as sodium, aluminum, titanium, barium, strontium, and certain rarer elements are found in plant ash.

tissue is fabricated from the soil. Quite the reverse is true. Fresh plant tissue generally carries only from .5 to 2.5 per cent. of mineral material. In spite of this, it is the mineral elements of nutrition that generally limit crop growth since a plant can always obtain, except in cases of drought or disease, unlimited amounts of carbon, hydrogen and oxygen.

8. Primary nutrient elements.—While all of the seven soil nutrients must be available that plants may grow normally, only four or five are likely to become limiting factors. The others are almost always in great sufficiency. These few, nitrogen, phosphorus, potassium, calcium and occasionally sulfur, receive as a consequence especial attention. They may limit growth because they are actually lacking or because their availability is low. These conditions often occur in the same soil.

Combined nitrogen exists in the soil to a large degree as a part of the partially decayed organic matter present therein.[1] As decay proceeds, small quantities of this nitrogen appear as ammonia in combination with some acid radical such as the chloride or sulfate or with the hydroxal group. Later, it is changed through further bacterial action to the nitrate form, united with some bases such as calcium or potassium. It is from this latter combination that most plants obtain the greater part of their nitrogen. These inorganic nitrogen compounds, present at any one time in a soil, are but a small proportion of the total soil nitrogen. The air both above the soil and that circulating within its pores has been the original source of all the combined nitrogen. Natural processes have facilitated the combination which has been necessary for such a transfer. The encouragement of such

[1] Certain rocks, particularly those of a sedimentary nature, carry considerable nitrogen. When such rocks weather, this nitrogen tends to become available. The organic matter, therefore, does not absolutely control the amount of nitrogen in a soil. Hall, A. D., and Miller, N. H. J., *The Nitrogen Compounds of the Fundamental Rocks;* Jour. Agri. Sci., Vol. II, Part 4, pp. 343-345. July, 1908.

fixation processes, especially those of a biological nature, is a feature of practical soil improvement.

Phosphorus has its origin in the mineral apatite ($Ca_5(PO_4)_3(Cl,F)$) and exists in the soil not only in this form but as tri-calcium phosphate ($Ca_3(PO_4)_2$), iron and aluminum phosphates ($FePO_4$ and $AlPO_4$) and in certain other inorganic complexes. It also exists in organic combinations of a constantly varying nature. It probably is utilized by the plant as a simple phosphate such as the mono- or di-calcium salt ($CaH_4(PO_4)_2$ and $Ca_2H_2(PO_4)_2$).

Potassium, as already stated, occurs in the soil in orthoclase and microcline ($KAlSi_3O_8$), in mica, especially muscovite ($H_2KAl_3Si_3O_{12}$), and in other aluminum silicates, both hydrated and non-hydrated. These complex forms supply potash to the soil solution and thus to the plant at a more or less rapid rate in the bicarbonate, carbonate, chloride, nitrate, and sulfate forms.

Calcium, while necessary in the soil as a nutrient, also functions as an amendment in that it seems to preserve a proper soil reaction. It is possible that this relationship is as much nutritive as strictly chemical. Calcium exists in the soil in many minerals, of which calcite, plagioclase feldspar, hornblende and augite are perhaps the most important. It is carried as an absorbed compound by kaolinite and similar materials. Calcium becomes available in the soil as the nitrate, bicarbonate, chloride, phosphate, and sulfate.

Sulfur is found in the soil in rather small amounts and generally forms a part of the organic matter. Inorganically it usually occurs as a sulfate combined with the common bases. In this form it is available to plants. The original source[1] of most of the soil sulfur has been pyrite (FeS_2), the

[1] Considerable sulfur is brought to the soil in atmospheric precipitation. From 5 to 150 pounds an acre a year have been reported. Wilson, B. D. *Sulfur Supplied to the Soil in Rain Water,* Jour. Amer. Soc. Agron., Vol. 13, No. 5, pp. 226-229. 1921.

commonest sulfide of this element. Although sulfur is no more abundant in the average soil than phosphorus, it is generally not considered as an extremely important fertilizing constituent.

It is interesting to note at this point the amounts of the above elements in ordinary mineral soils. Generally the nitro-

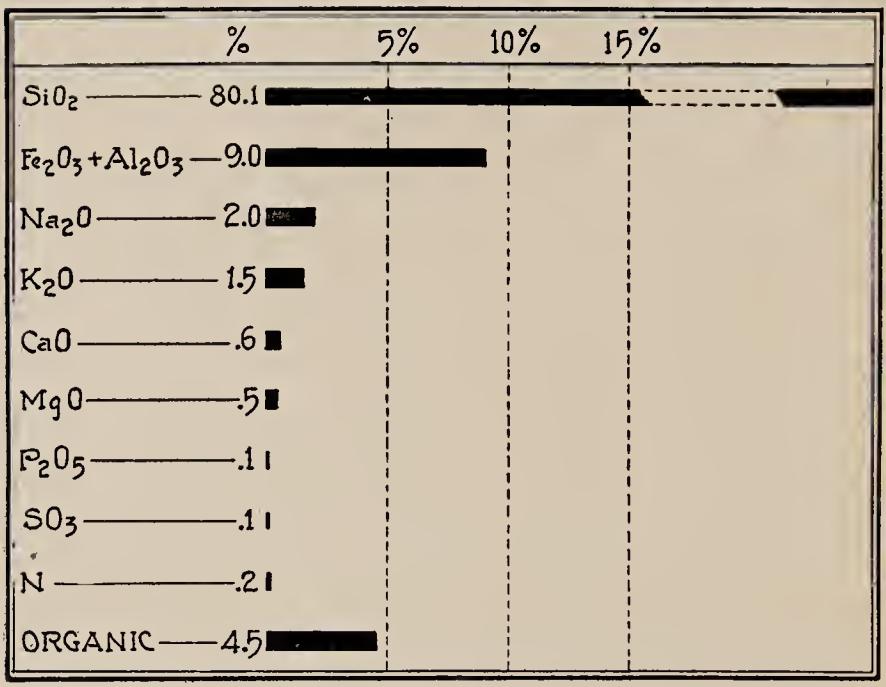


FIG. 2.—Chemical composition of a representative productive soil.

gen (N) may range from .1 to .2 per cent., the phosphoric acid (expressed as P_2O_5) from .05 to .30 per cent. and the potash (expressed as K_2O) from 0.5 to 2.0 per cent. Of the plant nutrients in the soil nitrogen, although usually present in small quantities, is relatively more available than is phosphoric acid or even potash. Phosphoric acid may be in the minimum because of its unavailability as well as because of the small quantity. Potash is commonly present in rela-

tively large amounts. Its occurrence in complex and insoluble silicates makes its availability of vital consideration. The presence of abundant organic matter may have much to do with the liberation of sufficient potash for vigorous plant growth.

The amount of lime (expressed as CaO) in soils is difficult to state with any degree of satisfaction because of a very wide range in composition. Some soils carry only a fraction of a per cent., while others, especially those formed under conditions where an originally high calcium content has been maintained or where calcium has accumulated, show as much as 10 or 12 per cent. The variability of the sulfur is much less. A range from .02 to .30 per cent. of sulfur (expressed as SO_3) will include most soils.

It is interesting at this point to note the average composition of thirty-five representative American surface soils[1], which were studied by the United States Bureau of Soils during a systematic investigation of the arable lands of the United States east of the Rocky Mountains. A comparison of these data with those setting forth the composition of the lithosphere [2] may be made with profit. (Table I, page 14.)

It is immediately noticeable that silicon, aluminum, and iron make up the greater portion of both soil and lithosphere and that the nitrogen, sulfur and phosphorus are particularly low in both cases. Magnesium, calcium, sodium, and potassium occur in fair amounts, especially in the earth's crust. It is noticeable also that the soil is much higher than the lithosphere in silicon, nitrogen, organic matter, and carbon but much lower in all of the other constituents. These differences have developed as a result of the losses and gains during soil formation.

[1] Robinson, W. O. *et al., Variations in the Chemical Composition of Soils;* U. S. Dept. Agr., Bul. 551. June, 1917.

[2] The Lithosphere refers to the solid portion of the earth, in this case to a depth of ten miles. Clarke, F. W., *Data of Geochemistry;* U. S. Geol. Survey Bul. 695, p. 33. 1920.

TABLE I

COMPARISON OF THE CHEMICAL COMPOSITION OF AMERICAN SURFACE SOILS WITH THAT OF THE LITHOSPHERE.

CONSTITUENTS [1]	35 AMERICAN SURFACE SOILS	COMPOSITION OF LITHOSPHERE
SiO_2	84.67	59.77
Al_2O_3	6.73	14.89
TiO_2	.66	.77
Fe_2O_3	2.53	6.25
MnO	.06	.09
Na_2O	.49	3.25
K_2O	1.03	2.98
CaO	.40	4.86
MgO	.27	3.74
P_2O_5	.09	.28
SO_3	.09	.28
Nitrogen	.07 a	—
Organic Matter	2.61 b	—
Carbon	1.51 c	.03

(a) Average of 22 soils only. (b) Average of 13 soils only.
(c) Calculated from the organic matter.

9. The soil and the plant.—As the soil considered agriculturally is essentially a medium for crop production, its rational study has to do with the consideration and application of such scientific principles as have a bearing on practical soil management. Anything that makes clearer the relationships between soil and crop has a proper place. Unless a scientific phase has a crop relation, either directly or indirectly, it need receive but scant consideration. The composition of the soil, its chemical and biological changes, its physical peculiarities and its reaction to certain additions must receive especial attention. More knowledge of the soil

[1] Soils contain many other elements, although in small amounts, such as chlorine, barium, cæsium, chromium, lithium, molybdium, rubidium, vanadium, etc. Robinson, W. O., *The Inorganic Constituents of Some Important American Soils;* U. S. Dept. Agr., Bul. 122. Aug., 1914.

will mean better systems of management and will allow the farmer to fulfill to a greater degree his duty to himself and to the State—the production of paying crops and the passing on to the next generation of a soil depleted as little as possible in fertility.

CHAPTER II

SOIL-FORMING PROCESSES

THE forces which have to do with soil formation are largely climatic in nature. They promote the physical and chemical breaking down of rock masses, they intermix there with the decaying organic matter and they shift the products from place to place. Even after the soil is apparently at rest and has become an effective agency in plant production, these same forces are still much in evidence. The physical and chemical evolutions through which mineral and organic materials at or near the earth's surface are passing due to natural forces are spoken of as *weathering*.[1] *Erosion* and *deposition* are terms referring to the natural translocations which soils and soil materials are frequently forced to undergo.

If a soil represents a condition more stable than the rock, the rock change is in that direction. If a soil presents constituents or conditions not wholly stable to the forces effective at that particular time, it in turn seeks a change by an alteration or an elimination. A cycle of development is thus set up proceeding from youth to adolescence and even into old age. According to conditions, soils may age rapidly or slowly. Rejuvenation may even occur, while cases of arrested development may exist for short periods.

10. Soil-forming processes classified.—While weathering, with the changes in form and composition which invariably accompany it, profoundly affects topography, it is very

[1] The term weathering is somewhat misleading since it comprehends forces other than those generally considered as weather. All of the forces involved, however, depend upon climatic conditions.

superficial in comparison to the earth's bulk. Nevertheless, the weathered mantle, in spite of its comparative insignificance, presents an effective medium for plant growth. The agencies of formation, therefore, demand more than the brief mention just given. These forces are geologic when the soil is being evolved, but once the soil materials are in place, the actions become localized and the influences may be considered as soil processes rather than more broadly geological.

The soil-forming processes[1], while diverse both in action and product, may be classified under two heads, mechanical and chemical. The former is often designated as *disintegration,* the latter as *decomposition.*

SOIL-FORMING PROCESSES

I. Mechanical (disintegration)
  A. Erosion and deposition.
    Water, ice and wind.[2]
  B. Temperature change.
    Differential expansion of minerals, exfoliation and frost.
  C. Biological influences.
    Plants and animals.
II. Chemical (decomposition)
  A. Oxidation and deoxidation.
  B. Carbonation and decarbonation.
  C. Hydration and dehydration.
  D. Solution.

11. The mechanical action of water.—From the time that that water as rain beats down upon the solid earth until it is finally discharged into the ocean, there to pound as waves upon the bordering lands, it is moving, sorting, and reworking the products of weathering. Water to erode must be

[1] For a complete and detailed discussion of soil formation, see Merrill, G. P., *Rocks, Rock Weathering and Soils;* New York. 1906. Also, Emerson, H. L., *Agricultural Geology;* New York. 1920.

[2] Gravity is generally included in this group. While indirectly of great significance in soil formation, its direct action is not of great importance and is adequately disposed of in paragraph 27.

armed. Its cutting power, therefore, depends on the amount of sediment that it carries and on its velocity of flow. Erosion by water deserves particular attention, as its denuding effects are very rapid when geologically viewed. Most of the changes in topography are due to such activity. The material swept away is partly in suspension and partly in solution.[1] The Appalachian Mountains, whose uplift was complete in Carboniferous times, have lost vastly more of their mass than now remains in view.

While most of the debris from the ancient erosive cycles has been changed to rock or has become a noticeable characteristic of ocean water, remnants persist. To these remnants rivers, lakes and oceans are making, year by year, substantial additions. The cutting, carrying and depositing activity of streams produce alluvial soils of which the Mississippi flood plain is a well known example. Deltas built into oceans, lakes and gulfs represent stream activity under different conditions, while uplifted continental shelves are often bedded with erosive products. The delta and marine soils of the Atlantic and Gulf coastal plains afford examples of the latter types of soil production. Even the pounding, grinding and sorting activities of waves in ocean and lake are no mean factors in the mechanics of soil formation.

12. Glacial action.—Ice at the present time, especially in temperate regions, is of little importance in soil formation. Nevertheless, at a comparatively recent date geologically, it had much to do with the preparation and deposition of soil materials over great areas in central and northern North America, northern Europe and the British Isles. During the Great Ice Age immense continental glaciers successively invaded these regions, much as the ice cap is over-

[1] The chemical denudation by streams is generally spoken of as *corrosion*. *Abrasion* is applied to the wear of the stream load upon its channel and of the particules in suspension upon themselves. *Erosion* is a broader term including corrosion and abrasion as well as transportation.

riding Greenland to-day. Of great thickness and weight and impelled southward by tremendous pressure, these ice sheets swept away the old soil mantle and ground the underlying rocks with irresistible energy. The heterogeneous debris, imbedded in the ice, only served to enhance the cutting power of the slowly moving mass. Hundreds of square miles were covered and as the ice was often several thousand feet thick, mountains as well as hills were over-ridden. (See Fig. 3.)

In the melting back of these tremendous ice sheets, the accumulated debris was of necessity left behind. When the ice retreat was rapid, the deposit was comparatively thin and uniform. When a halt occurred, the material was left in irregular hummocks. It is hardly necessary to state that the soil developed from the former deposit is the more important agriculturally, due to its level topography and wide extent. The area of the latter is fortunately small. The streams flowing from the ice fronts were no insignificant feature of the glacial phenomena. Such streams were heavily laden with sediment, which was distributed far and wide in regions miles beyond the ice front.

In whatever manner the glacial debris was laid down it is necessary to note that such deposits were soil material, not soil. Chemical action in all its complexity and the intervention of plants and animals, especially the former, were necessary before a true soil could be born, a soil still in its youth and covering in the United States alone over 500,000 square miles. (See Fig. 3, page 20.)

13. The influence of wind.—Wind, like water and ice, has both cutting and carrying power. The fluting of rocks, the polishing of stones, and the undermining of cliffs are of such frequent note as to require but brief mention. There seems no escape from the conclusion that wind is engaged in rock disintegration. Its geological function in arid regions seems similar to that of running water in humid lands.

It is, however, as a transporting agency of fine materials

FIG. 3.—Sketch map of North America showing the approximate southward extension of the great ice sheets and the three centers of accumulation.

that the wind is of especial importance in soil formation. The movement of sand and dust in both humid and arid regions is almost incessant. In desert storms 200 tons of materials have been known to float over every acre of land. The finer particles travel for miles in a very short time. Southern Italy has received as much as one inch of dust from Africa during a single storm. The movement of sand dunes is but another evidence of the transporting power of air in motion.

Wind as an agency in soil formation would perhaps receive much less attention were it not for the existence of large areas of a certain silty soil called *loess*. This soil exists along the Rhine both in France and Germany, in southern Russia, in Roumania, in China and in central United States. This material, as well as the *adobe* of our arid Southwest is considered as largely wind laid. Since the loess is highly fertile and of great agricultural importance, added attention is thus directed towards wind as a soil-forming agency. (See Fig. 4.)

14. Change in temperature.—Variations of temperature, especially if sudden or wide, greatly augment the denuding actions of water, ice, and wind. Rocks and soil become heated during the day and at night often cool much below the temperature of the air. This warming and cooling is particularly effective as a disintegrating agent. Rocks are mineral aggregates, the minerals varying in their coefficients of expansion. With every temperature change differential stresses are set up, which eventually must produce cracks and rifts, since the minerals never assume their original position. Incipient foci for further physical and chemical change are thus established. Although the expansion coefficient of rock is low, it must be remembered that very large surfaces are involved. Moreover, it is the multiplicity of the rifts rather than their magnitude that is important.

The influence of temperature change is manifested on rocks in another way. Due to slow conduction the outer surface of a rock often maintains a markedly different temperature

than the inner and more protected portions. This differential heating tends to set up lateral stresses which may cause the surface layers to peel away from the parent mass. This phenomena is spoken of as exfoliation. The differential expansion

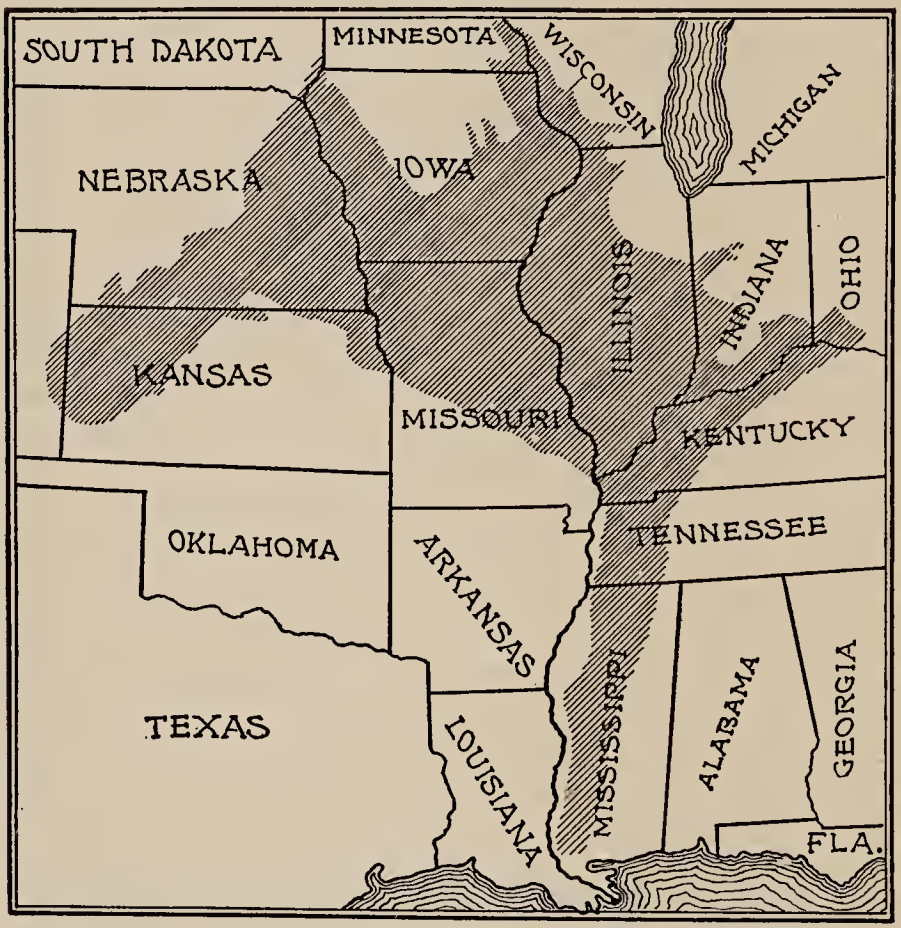


FIG. 4.—Approximate distribution of loess in central United States.

of the rock minerals of course plays a part in this disintegration, although exfoliation readily occurs in rocks which are more or less homogeneous. While this form of weathering may go on alone, it is much accelerated by chemical action and the prying of freezing water.

One peculiarity of pure water is that its maximum density occurs at 39.2 deg. F. From this point the volume increases as the temperature is lowered. Ice, which forms at 32 deg. F., thus occupies a greater space than the water from which it was derived. The force developed by freezing is equivalent to about 150 tons to the square foot or a pressure of 141 atmospheres. The cracks and crevices of surface rocks in humid regions are from time to time filled with moisture. Rocks below the surface contain water continuously. The change of this water from a liquid to a solid always produces marked disintegration. Mountain-top rubble, talus slopes, alluvial fans, and similar formations are evidences of such action. The load of sediment carried by streams is often due to the prying action of temperature change, especially where crevice water is present.

This action of temperature is by no means ended when a soil is produced. Freezing and thawing is of tremendous importance in bettering the physical condition, especially of heavy soils. It is to such forces that the farmer owes the good tilth of his land. In addition it must be noted that the rapidity of chemical change is largely a function of temperature. The concentration of the soil solution and the availability of the nutrient elements thus come under the influence of this apparently simple force.

15. Plants and animals.—While plants and animals unite their activities with the processes already mentioned, their influence is confined largely to the soil and the soil material. Simple plants such as mosses and lichens grow upon exposed rock, there to catch dust and dirt until a thin film of highly organic material accumulates. Higher plants sometimes exert a prying effect on rock, which results in some distintegration. Such influences, however, are of but little import in soil formation compared to the drastic activities of water, wind, ice and temperature change.

In the soil, roots by their ramifications promote aëration

and drainage, as well as an accumulation and distribution of organic materials. Lichens, mosses, and algæ play their parts in a similar manner. It must be noted, however, that while plants tend to preserve and improve the soil tilth, their action in this respect is not wholly physical. Decay due largely to bacterial action is necessary before the accumulated organic matter can improve to any marked degree the physical condition of the soil. This is only one of the many examples illustrating the coöperation of physical and chemical changes incident to soil formation.

Animals influence the soil physically by their burrowing propensities. Gophers, squirrels, ants, and the like mix and open up the soil, thus providing for the circulation both of air and water. Other soil forces, both physical and chemical, are markedly encouraged thereby. Earth worms produce similar effects. They not only pass great quantities of soil through their bodies, but they carry much to the surface. This has been estimated as amounting to one or two surface inches in a decade. Man also is producing important physical changes on the soil and soil material. The plowing under of green-manures, crop residues and farm manure, the addition of lime and fertilizers and the tillage incident to cropping have much to do with the physical changes, which are continually occurring in the soil.

16. Oxidation and deoxidation.—Scarcely has the disintegration of rock begun than its decomposition is also apparent. This is especially noticeable in humid regions where the chemical and physical processes of soil formation are particularly active and markedly accelerate each other. Of the chemical forces, oxidation is usually, especially near the surface, the first to be noticed. It is particularly manifest in rocks carrying iron in the sulfide, carbonate or silicate forms. The sulfide, although widespread, is less important in promoting rock decay than the other combinations. The oxidation of iron in any form is indicated by a discoloration of the

affected rock, which from the first is streaked with iron oxide. The mica, amphibole, pyroxene and garnet groups are particularly affected, until, as the process continues, these minerals waste away into unrecognizable forms so weakening the rock as to cause it to crumble easily. The way is now open for vigorous chemical and physical changes of all kinds. Oxidation may be illustrated chemically, using olivine as the mineral decomposed. It is to be noted that the first step is the assumption of water and the production of serpentine and ferrous oxide. The latter quickly changes to the susquioxide.

$$3MgFeSiO_4 + 2H_2O = H_4Mg_3Si_2O_9 + SiO_2 + 3FeO$$

Olivine — Water — Serpentine — Silica — Ferrous Oxide

$$4FeO + O_2 = 2Fe_2O_3 \text{ (red)}$$

Ferrous Oxide — Oxygen — Ferric Oxide

Deoxidation is the reverse of oxidation, being a reduction of the amount of oxygen present in the compound. With hematite it might occur as follows:

$$2Fe_2O_3 - O_2 = 4FeO$$

Ferric Oxide — Oxygen — Ferrous Oxide

In a similar way, other oxides and salts may be reduced by the withdrawal of oxygen. This action occurs in poorly drained soils or in soil very rich in organic matter. It is generally apparent in forest soils just below the organic surface layer. Here the leaching downward of small quantities of organic acids has been sufficient to develop a definite greyish zone, varying both in color and depth. The bleaching of sands, shales, sandstones, and clays may often be due to deoxidation rather than the actual removal of ferric iron. No great importance need be attached to deoxidation either in soil formation or in the chemical processes which continue to affect the soil after it is definitely developed.

17. **Carbonation.**—The process of oxidation is almost always accompanied by the action of carbon dioxide. This gas is a constituent of the air and is a product of the organic decay which vigorously progresses in most soils. It occurs in large amounts in rain water, especially in warm climates. It increases the solvent action of water by actively engaging in chemical reactions, producing carbonates and bicarbonates with the various rock and soil bases. The decomposition of orthoclase and muscovite mica into kaolinite and carbonates is as follows:

$$\underset{\text{Orthoclase}}{2KAlSi_3O_8} + \underset{\text{Water}}{2H_2O} + \underset{\substack{\text{Carbon}\\\text{Dioxide}}}{CO_2} = \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + \underset{\substack{\text{Potassium}\\\text{Carbonate}}}{K_2CO_3} + \underset{\text{Silica}}{4SiO_2}$$

$$\underset{\text{Muscovite}}{2H_2KAl_3Si_3O_{12}} + \underset{\substack{\text{Carbon}\\\text{Dioxide}}}{CO_2} + \underset{\text{Water}}{4H_2O} = \underset{\text{Kaolinite}}{3H_4Al_2Si_2O_9} + \underset{\substack{\text{Potassium}\\\text{Carbonate}}}{K_2CO_3}$$

Under certain conditions decarbonation may occur. Whenever the processes of weathering produce either mineral or organic acids carbonates are rapidly decomposed. The presence of unsaturated aluminum silicates may also rapidly promote decarbonation by absorbing the base and liberating the acid radical. This latter reaction is of especial importance in soil.

18. **Hydration.**—All the chemical transformations above discussed depend on the presence of a certain amount of water, especially if rapid changes are to occur. The illustrative reactions already cited indicate this. Oxidation proceeds but slowly in a dry atmosphere, water being necessary as a catalytic agent. In the carbonation of the potash of orthoclase and mica, water enters into the reactions, producing not only kaolinite but also potassium hydroxide, which is later changed to the carbonate.

Water functions in the chemical changes of rock and soil

in another way—as water of combination.[1] The process is called hydration. While hydration usually proceeds or accompanies oxidation and carbonation, thus making them possible, it often, unlike these transformations, occurs at great depths and may be practically the only change that the rock minerals have undergone. Many minerals, especially the olivine, feldspar and mica groups, are so affected. They become soft and lose their luster and elasticity on the assumption of this chemically combined water. Considerable increase of bulk occurs during the transition of the rock to soil. The latter change has no small physical significance. This hydration is particularly effective in encouraging other kinds of chemical decay. In addition to the examples already cited, the change of hematite to limonite, which occurs to a greater or less degree in every soil where the sesquioxide is present, is worthy of note:

$$\underset{\text{Hematite}}{2Fe_2O_3} + \underset{\text{Water}}{3H_2O} = \underset{\text{Limonite (yellow)}}{2Fe_2O_3 \cdot 3H_2O}$$

When the products of weathering dry out due to varying weather conditions, dehydration may occur. Thus limonite may readily reduce to a lower hydrate or to hematite.

19. **Solution.**—It is quite evident that while weathering and erosion produce many compounds of a very complex character, there is a tendency toward simplification and, as water is universally present, some solution occurs. Such bases as calcium, magnesium, sodium and potassium are found in the water that circulates in rocks, soil materials and soils. These bases, when in solution, are generally combined as chlorides, phosphates, nitrates, carbonates, and the like. Carbon dioxide intensifies to a marked degree the solvent action of water and consequently increases its power as a weathering agent. The

[1] Note carefully the difference between hydration and the production of an hydroxide. The former is the more important as a soil phenomenon

atmosphere carries about .03 per cent. of carbon dioxide by volume, while considerable amounts are brought down on rocks and soil by rain and snow. Traces of nitric and sulfuric acid are also found in rain water. The carbon dioxide produced within the soil by decaying organic matter keeps the concentration of this gas high at points where it can act most effectively.

Solution,[1] accelerated both by mechanical and chemical means, is of particular importance in two directions. In the first place, it allows a continual loss of plant nutrients not only as the soil is being formed but after it becomes a proper medium for plants. This constant drain accounts for the deficiency of certain elements in the soil and the need in certain cases of such additions as lime and fertilizers. On the other hand, this solution, however wasteful, is necessary since plants absorb nutrients from the soil only in soluble form. The concentration and composition of the materials in the soil water is thus a function of solution, which is a culmination of the activities of the soil processes already discussed.

20. General statement of soil formation.—By a very complicated coördination the mechanical and chemical forces of weathering reduce the solid rock to small fragments and mix therein the necessary organic matter. The process slowly proceeds until a suitable medium for the growth of higher plants is produced. As a rule, the chemical processes are incomplete and all stages of decay are exhibited. This is fortunate, as solution may thereby continue to renew the nutrients in the soil-water for a long period and thus maintain the continuous productivity of the soil.

The products of disintegration and decomposition are commonly classified into two general groups, *sedentary* and *trans-*

[1] While the formula for water is generally given as H_2O the molecule is not as simple as this, being at low temperature as high as $(H_2O)_4$. The remarkable power of water as a solvent may be due to extra oxygen valences as well as to the high dielectric constant which favors ionization, thus hastening chemical reaction.

ported. The former remains in place, being the rock residuum in which organic matter accumulates. Residual clay is an example. The second group, on the other hand, in addition suffers transportation and is represented by the soils arising from glacial drift, alluvial accumulations, aëolian deposits, and the like. In the first case, the soil is derived from a single lithologic unit; in the second place, the assorted and blended materials are from many sources. A general statement of the formation of a residual soil [1] is obviously the easier to

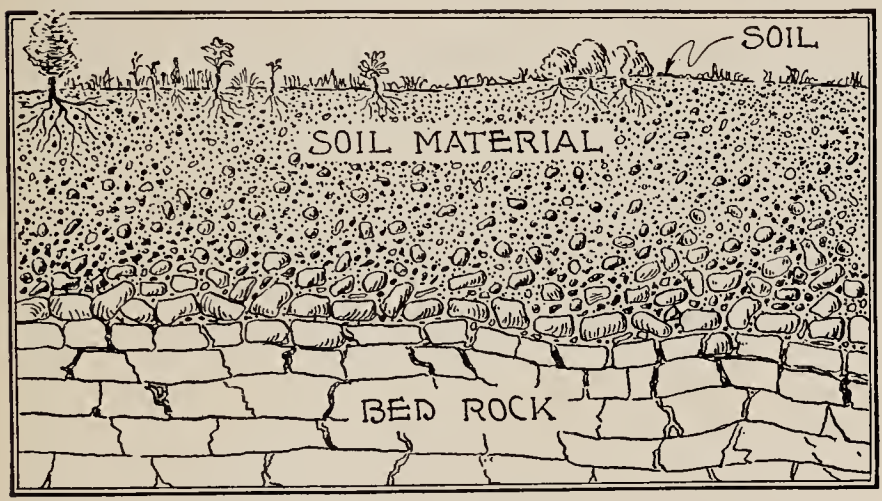


FIG. 5.—The gradual transition of country rock into residual soil by weathering *in situ*.

make. Such a statement adequately covers every process in the production of a transported soil except the disintegration, assortment, and solution due to translocation. (See Fig. 5.)

"The changes that a rock undergoes in forming a residual soil are first a physical breaking down, accompanied by certain chemical transformations, which consist in the hydration of a portion of the feldspars, micas and similar minerals; the

[1] Buckman, H. O., *The Formation of Residual Clay;* Trans. Amer. Cer. Soc., Vol. XIII, p. 362. Feb., 1911.

oxidation and hydration of a part of the combined iron; and a carbonation and solution of a large proportion of the soluble bases. These processes are hastened and the whole mass evolved into a soil by the admixture and decay of certain amounts of organic matter."[1]

21. Variation of soil formation with climate.—It may be seen readily that the activity of the various soil-forming agencies will fluctuate with climate. A comparison of weathering and erosion in an arid and a humid region will illustrate the point at issue. Under arid conditions, the physical forces will dominate and the resultant soil will be coarse. Temperature changes, wind action and the influence of animals will be almost the sole agents. In a humid region, however, the forces are more varied and practically the full quota will be at work. Chemical decay will accompany disintegration and the result will be shown in the greater fineness of the product. The separate minerals will also show the change of color and loss of luster so characteristic of chemical action. A granite, for example, is a very insoluble rock, compared with a limestone, and in a humid region, where chemical agencies are dominant, it will be markedly more resistant. If, however, these rocks are exposed in an arid region, where physical weathering is potent, the results will be entirely different. The limestone, being homogeneous, will not be affected markedly by temperature changes, but the stresses set up in granite must ultimately reduce it to fragments.

Arid soils, besides being rather coarse, are generally rather uniform, there being little difference between soil and subsoil. The soils of humid regions are usually of fine texture, particularly in residual sections, since the chemical agencies have

[1] It is well to remember that synthetic processes as well as forces of simplification and dissolution are active in soil formation. The soil features that result are of two kinds, hereditary and acquired. The former develop through geological forces, the latter through the activity of true soil processes.

been so active. Various colors may develop because of oxidation, hydration, and the presence of organic matter. Such soils usually are not excessively deep, and are likely to be underlaid by subsoils heavier than the surface. The general physical condition and tilth of arid soil is uniformly better than that of regions of plentiful rainfall.

Chemically, because of less leaching, the arid soils contain more of the important mineral elements. The following analyses bring out the differences in a striking manner:

TABLE II

COMPARATIVE ANALYSES OF ARID AND HUMID SOILS[1]

CONSTITUENTS	ARID SOILS AVERAGE OF 313 SAMPLES	HUMID SOILS AVERAGE OF 466 SAMPLES
Insoluble	77.82	88.24
Al_2O_3	7.89	4.30
Fe_2O_3	5.75	3.13
CaO	1.36	.11
K_2O	.73	.22
P_2O_5	.12	.11
MgO	1.41	.23
Volatile	4.94	3.64

It is immediately apparent that the arid soil is poorer in silica than the humid soil, but richer in iron and alumina, indicating a less weathered condition of the feldspars. Due to a greater amount of leaching, the humid soil is much lower in phosphoric acid, lime, magnesia, and potash. The humus in arid soils is somewhat lower than in the soils under better

[1] Hilgard, E. W., *Die Boden arider und humider Länder;* Internat. Mitt. Bodenkunde, Bd. I, pp. 415-529. 1912.

conditions of rainfall, as one would naturally expect. The amount of easily soluble material is higher in arid regions, due to the lack of rain and the tendency for soluble salts to accumulate. Biologically, organisms are active at greater depths[1] in arid than in humid regions, because of the loose structure of arid soils and because of their good aëration. Such soils are seldom water-logged except from improper irrigation. In humid regions bacterial action is limited very largely to the surface foot of soil, since only there are the aëration and the food conditions adequate. The intensity of biological activity in arid soils is very largely governed by moisture, and when moisture conditions are satisfied, bacterial changes may be expected to take place rapidly.

22. Special cases of soil formation.—Having compared the weathering of granite and limestone under different climatic conditions, it is interesting to note the quantitative chemical changes of these rocks as they are reduced residually to soil under humid conditions. The following analyses[2] indicate the elements that are likely to be lost to the greatest extent during the process. (See Tables III and IV, page 33.)

The soil resulting from the decay of the granite was a deep red clay, with numerous quartz grains present. The soil from the limestone was very plastic and high in silicate silica. Leaching has probably gone on to a very great extent in both soils. It is noticeable in both cases that the bases, such as calcium, magnesium, sodium, and potassium, have suffered severe losses. The carbonate has almost wholly disappeared from the limestone clay, indicating that a residual soil from such a rock will probably need an application of lime. (See Figs 6 and 7, pages 34 and 35.)

[1] Lipman, C. B., *The Distribution and Activities of Bacteria in Soils of the Arid Region;* Univ. Calif., Pub. in Agr. Sci., Vol. I, No. 1, pp. 1-20. 1912.

[2] Merrill, G. P., *Weathering of Micaceous Gneiss;* Bul. Geol. Soc. Amer., Vol. 8, p. 160. 1879.

TABLE III

FRESH GRANITE AND ITS RESIDUAL CLAY

CONSTITUENTS	ROCK	SOIL	PERCENTAGE LOST [1]
SiO_2	60.69	45.31	52.45
Al_2O_3	16.89	26.55	.00
Fe_2O_3	9.06	12.18	14.35
CaO	4.44	.00	100.00
MgO	1.06	.40	74.70
K_2O	4.25	1.10	83.52
Na_2O	2.82	.22	95.03
P_2O_5	.25	.47	.00
Ignition	.62	13.75	gain

TABLE IV

VIRGINIA LIMESTONE AND ITS RESIDUAL CLAY [2]

CONSTITUENTS	ROCK	SOIL	PERCENTAGE [1] LOST
SiO_2	7.41	57.57	27.30
Al_2O_3	1.91	20.44	.00
Fe_2O_3	.98	7.93	24.89
CaO	28.29	.51	99.83
MgO	18.17	1.21	99.38
K_2O	1.08	4.91	57.49
Na_2O	.09	.23	76.04
P_2O_5	.03	.10	68.78
CO_2	41.57	.38	99.15
H_2O	.57	6.69	gain

[1] The percentage loss of any constituent is calculated as follows:

$$\frac{A \times 100}{B \times \frac{C}{D}} = X \qquad 100 - X = \% \text{ Lost.}$$

A = % any constituent in residual material.
B = % same constituent in fresh rock.
C = % of the constant constituent in residual soil.
D = % of the constant constituent in fresh rock.

[2] Diller, J. S., *Educational Series of Rock Specimens;* U. S. Geol. Survey, Bul. 150, p. 385. 1898.

The analyses indicate that the soil from the granite does not differ greatly from the original rock, except in the loss of bases, assumption of water, and increase of organic matter. The soil from the limestone presents greater differences, due

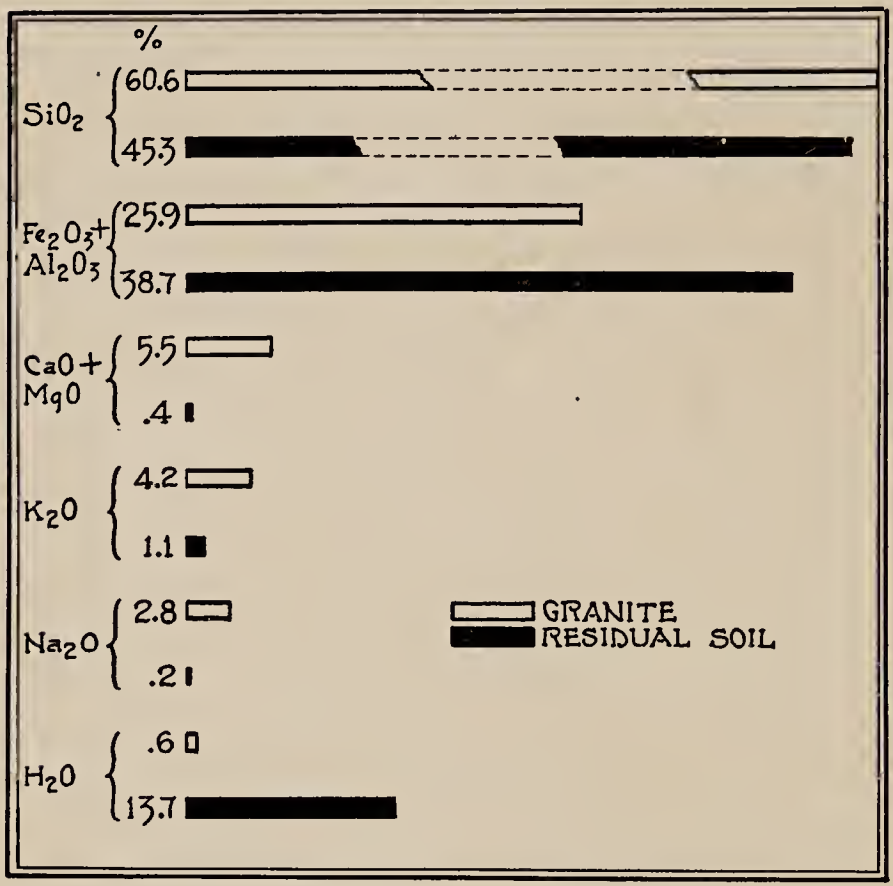


FIG. 6. — Diagram showing the composition of fresh granite and its residual soil. Note the marked hydration of the soil.

to the disappearance of the calcium carbonate. The analyses of the two soils resemble each other rather closely in spite of their widely different sources. Since weathering, especially residual weathering, causes a loss of basic materials and

thereby favors the accumulation of silica, alumina and iron, all soils as they age tend to approach each other in chemical composition. Yet, owing to a difference in the adjustment of the forces at work and to the time element, no two soils

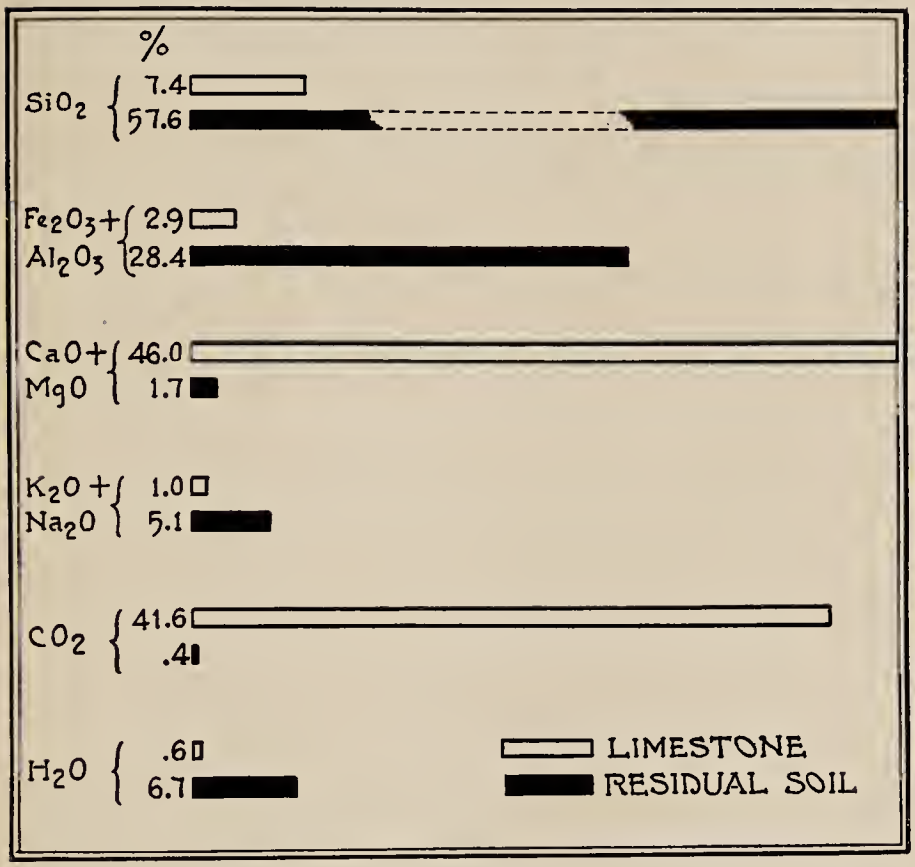


FIG. 7.—Diagram showing the composition of limestone and its residual soil. Note the excessive loss of lime and carbon dioxide in soil formation.

will ever be exactly alike. Soils will differ from the original rock and from one another according to the intensity and character of the weathering and erosive forces and to the constitution of the parent minerals.

23. Red and yellow colors of soil.[1]—The presence of iron, as already noted, is a very important factor in rock weathering, and the discoloration due to its presence is an unfailing indication of chemical decay. The iron in minerals occurs usually as ferrous oxide, which is soluble, especially if the water circulating among the rock fragments carries carbon dioxide. When this water comes in contact with the air its excess of carbon dioxide is discharged and the oxides and carbonates of iron are deposited. Under this condition oxidation goes on rapidly, and the iron passes to the ferric state and becomes insoluble. Thus it may be seen that iron imparts a fatal weakness to rocks and minerals in which it exists, due to its solubility; yet from the oxidation that it undergoes it tends to persist and accumulate in soils. The more iron a mineral or rock contains the more susceptible it is to weathering.

The red and yellow soils of the southern states frequently excite comment, especially as a difference in fertility is popularly recognized, the red surface soil with a red subsoil being considered more fertile than a similar soil with a yellow subsoil. This is probably due to differences in hydration of the iron oxides.[2]

The soil temperatures, particularly in tropical and subtropical regions, have first tended fully to oxidize and hydrate the iron, and then to dehydrate the soil at the surface into the deep red color, leaving the subsoil yellow and causing the contrasts so markedly evident. Soils having a yellow surface soil are generally considered to be older and more weathered than those where the red is well developed. When

[1] Robinson, W. O., and McCaughey, W. J., *The Color of Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 79, p. 21. 1911.

[2] Crosby, W. O., *Colors of Soils;* Proc. Boston Soc. Nat. Hist., Vol. 23, pp. 219-222. 1875. Merrill, G. P., *Rocks, Rock Weathering and Soils;* p. 375. New York, 1906. Van Bemmelen, J. M., *Beitrage zur Kenntnis der Verwitterungsprodukte der Silicate in Ton-, Vulkanischen-, und Laterite-Boden;* Zeit. Anorg. Chem., Bd. 42, Steite 290-298. 1904.

these old residual soils are poorly drained a well defined mottling develops, especially in the subsoil, due to the irregularities of aëration.

The compositions of hematite and of the limonite group indicate the possibility of a progressive change from red to yellow by hydration:

Hematite	Fe_2O_3	Red
Limonite Group	Turgite $2Fe_2O_3 . H_2O$	↑
	Goethite $Fe_2O_3 . H_2O$	‖
	Limonite $2Fe_2O_3 . 3H_2O$	‖
	Xanthosiderite $Fe_2O_3 . 2H_2O$	‖
	Limnite $Fe_2O_3 . 3H_2O$	↓ Yellow

24. Practical relationships of weathering.—Soil-forming processes fortunately remain intensely active after the soil has been produced. The physical agencies especially tend to loosen and fine the soil, contributing largely to its tilth. The farmer encourages such influences by plowing his land and by other tillage operations. The addition of organic matter is another means whereby these physical changes may be influenced. Granulation in a clay soil is due almost entirely to natural agencies. Were it not for such activities the soil would soon become physically unfit as a foothold for plants. The continual chemical changes, culminating in solution, provide the soil-water with plant nutrients not only in suitable concentration but in correct proportion. By slow processes, over geologic periods, Nature has provided us with soil and by the same slow processes Nature is attempting to maintain the fertility of her creation. The encouragement and control of such agencies is of no small moment in practical soil management.

CHAPTER III

THE GEOLOGICAL CLASSIFICATION OF SOILS

WEATHERING must be considered as affecting soils, whether they are in motion or at rest. This gives rise to two general classes of soil materials—those that have not been shifted far from their original situation and those that have suffered considerable translocation. These two general groups, designated as sedentary and transported, are subject to subdivision as follows:[1]

- Sedentary
  - Residual
  - Cumulose
- Transported
  - Gravity ..... Colluvial
  - Water .... Alluvial, Marine, Lacustrine
  - Ice ..... Glacial
  - Wind ..... Æolian

25. Residual soils.[2]—This group of soils covers wide areas of arable regions, especially in the tropics and subtropics, and comes from many kinds of rock. Residual soils are, in the main, old soils, usually the oldest with which we deal in agricultural operations, although some residual soils are comparatively young. Since they are formed *in situ*,

[1] Merrill, G. P., *Rocks, Rock Weathering and Soils*, p. 288; New York, 1906.

[2] For a full discussion of the origin and characteristics of the soils of the United States see Marbut, C. F. *et al.*, *Soils of the United States;* U. S. Dept. Agr., Bul. 96. 1913. For the soils of the Southern States, consult Bennett, H. H., *The Soils and Agriculture of the Southern States;* New York, 1921.

the rocks that underlie them, if sound, often given some clue to the character and composition of the parent material.[1] Under such conditions the changes that a rock undergoes in forming a soil may be studied to the best advantage.

Residual soils are usually non-stratified and present a heterogeneous mass of material, grading from a true soil, with its normal content of organic matter, downward through the typical soil material to the unweathered country rock below. Since such soil has been subject to leaching for long periods, a very large amount of its soluble materials have been washed out, tending to leave high percentages of the persistent elements, such as silica, iron and aluminum. The preceding discussion of soil formation has already emphasized this phase sufficiently.

The great age of residual soils has given opportunity for very thorough oxidation, so that much of the iron has changed to hematite or to the hydrated limonite group. The yellow color of the latter group is indicative of greater age than the former. Since almost all soil material contains considerable iron the prevailing colors of residual soils are reds and yellows, depending on the degree of oxidation and hydration. Grays, browns, and blacks often occur, however, where oxidation has not progressed or where organic matter is present in amounts sufficient to mask the iron coloration.

As residual soils have been subjected to intense physical and chemical weathering, the particles have been reduced to a very fine state of division. Over residual areas the heavier types, such as silt loams, clay loams and clays predominate. Sands and sandy loams may occur, however, when the parent rock carried considerable quartz and a low percentage of clay-producing minerals, such as feldspar, hornblende and augite. Soils from limestones, granites, and

[1] Residual soils are not always derived from rock similar to that directly underlying the soil as is often assumed. When the present bed rock is much different from the stratum which gave rise to the soil, the soil is said to be "inherited."

gneiss [1] are generally clayey in nature, although loams and even stony loams may occur if the limestone was sandy or cherty and if the igneous rocks carried much quartz. Dolomites weather more slowly than limestone and often give rise to gravelly and stony types. Sandstone of course produces sandy soils, although a soil from an argillaceous sand-

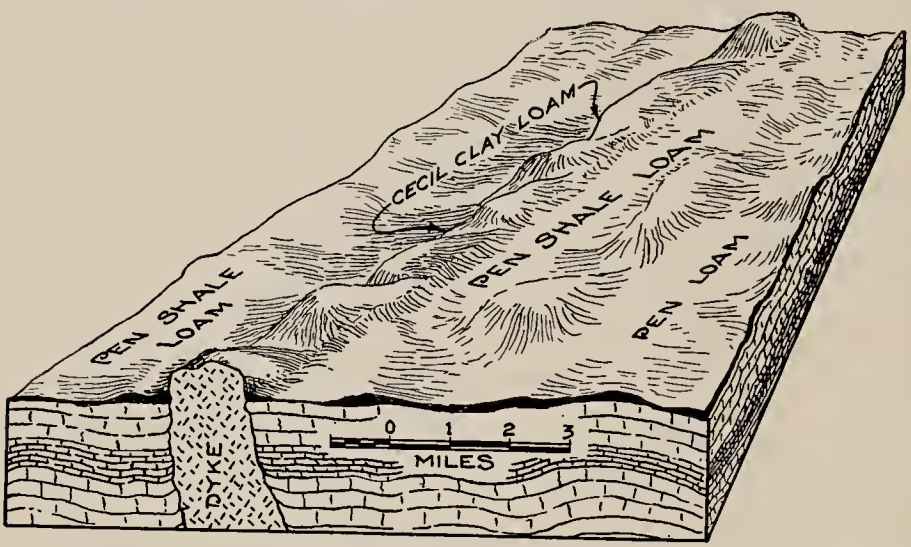


FIG. 8.—Diagram showing the relationship between the underlying rocks and the overlying residual soils. Gettysburg, Pa. (After Emerson.)

stone may be rather heavy. Quartzite and slaty soils are generally shallow, and unfavorable, both in texture and fertility, for crop growth. Soils from basic igneous rocks, such as diorite and basalt, generally produce sticky reddish or yellowish clays containing little quartz. Rocks that carry considerable mica, such as schists, give rise to highly micaceous soils.

[1] For a complete discussion of the influence of various parent rocks on the resultant residual soil see Emerson, H. L., *Agricultural Geology*, Chap. IV; New York, 1920.

The following analyses[1] show the general chemical character of surface residual soils and the variations that may be expected:

TABLE V

CONSTITUENTS	1	2	3	4
SiO_2	66.49	76.71	74.33	70.99
Al_2O_3	17.11	12.85	11.00	11.39
Fe_2O_3	7.43	2.81	4.64	4.23
TiO_2	1.02	.41	1.04	1.28
CaO	.36	.08	1.13	.93
MgO	.31	.29	.69	1.08
K_2O	.62	3.26	1.57	2.71
Na_2O	.16	.39	1.53	.82
P_2O_5	.17	.05	.16	.19
SO_3	.07	.12	.15	.34
Organic matter	1.26	1.78	1.99	.93

The organic matter of residual soils largely depends, in amount and condition, on climatic factors. If rainfall and temperature, for example, are favorable for the rapid and continued development of a natural vegetation the soil will be rich in humus, so rich at times as to mask to a certain extent the red color so characteristic of such soils. If plants do not grow well on this soil, however, it will be low in organic matter and probably in poor physical condition. Residual soils vary greatly in their general characteristics, especially as to crop productivity.

Residual soils are of wide distribution in the United States, particularly in the eastern and central parts, although great

[1] Robinson, W. O., *The Inorganic Composition of Some Important American Soils;* U. S. Dept. Agr., Bul. 122, Aug. 1914.

1. Cecil clay, from granite and gneiss. Charlotte, N. C.
2. York silt loam, from schists. Bethany, S. C.
3. Penn silt loam, from sandstone. Morristown, Pa.
4. Hagerstown loam, from limestone. Conshohocken, Pa.

areas are found in the West as well. A glance at the soil map of this country shows four great eastern and central provinces—the Piedmont Plateau, the Appalachian Mountains and Plateaus, the Limestone Valleys and Uplands, and the Great Plains Region. The first three groups alone occupy 10 per cent. of the area of the United States. The age of these soils varies in the order named, showing that, while they are very old as compared with other soils yet to be discussed, there may be vast periods of geologic time between their beginnings. As a matter of fact, there is probably a greater difference in age between the soils of the Piedmont Plateau and those of the Great Plains Region than has elapsed since the latter were formed. (See Fig. 9.)

26. Cumulose soils.—At relatively recent periods shallow lakes, ponds, and basins have been formed, partly by stream action, partly by marsh conditions along sea or lake coasts, or by glaciation, a common origin in northern United States and Canada. The highly favorable moisture relations along the banks of such standing water has encouraged the growth of many plants, such as algæ, mosses, reeds, flags, grass, and even larger types of vegetation. These plants thrive, die and fall down to be covered by the water in which they grew. The water shuts out the air, prohibits rapid oxidation, and thus acts as a partial preservative. The decay that does go on is largely through the agency of fungi and anaërobic bacteria, that break down the tissue, and liberate certain gaseous constituents. As the process continues the organic mass becomes dark or even black in color.

Accumulations of this nature are dotted over the entire country. Their size may vary from a few acres to several thousand. Along streams the old abandoned beds offer ready opportunity for the beginning of such accumulations. Marshes either salt or fresh often contain such deposits. Shallow basins produced by the scraping or damming action of glaciers are frequently occupied by such material. In the

last named case the beds are more or less independent of topography, and may be found on hillsides as well as in lower lands.

Cumulose materials may be grouped under two heads, peat and muck. The only difference is in their state of decay. In peat the stem and leaf structure of the original plants can still be detected, and identification is quite possible. In muck, however, the plant tissue has lost its identity as such and is merged into a complicated and indefinite mass of organic material.[1]

The composition of peat and muck may be much altered by the washing-in of mineral matter. In some cases the beds may be from 90 to 95 per cent organic, while in other cases, due to this foreign material, the percentage may drop as low as 20 per cent giving a black or swamp marsh mud.

The analyses given illustrate the composition of some representative cumulose soils. (See table VI, page 44.)

Peat and muck are often of large extent [2] and become of extreme value when drained, especially if they are near a good market. They are of peculiar value in trucking operations, being adapted to such crops as onions, celery, lettuce, and the like. Usually they must not only be provided with drainage, but must also be treated with fertilizers carrying

[1] The term "muck" is often used interchangeably with peat. Technically it is best to limit the former term to those peats which are very thoroughly decomposed or contain a high proportion of mineral matter. Chemically muck is often used in reference to soils containing from 20 to 50 per cent. of organic matter, while peat is confined to soils in which the amount of organic constituents is above 50 per cent. According to such a definition most cumulose soils are peats instead of muck. The term "muck" is so popular, however, that in the United States its use will continue in spite of the technical distinctions that have been established.

[2] Alway reports the following figures:

Germany	5,000,000 acres	Wisconsin ...	3,000,000 acres
Sweden	12,000,000 "	Ohio	175,000 "
Minnesota ...	7,000,000 "	Canada	22,000,000 "

Alway, F. J., *Agricultural Value and Reclamation of Minnesota Peat Soils;* Minn. Agr. Exp. Sta., Bul. 188, 1920.

TABLE VI

COMPARATIVE CHEMICAL COMPOSITION OF A PRODUCTIVE MINERAL SOIL AND CERTAIN REPRESENTATIVE PEAT AND MUCK SOILS.

Soils	Organic Matter	Mineral Matter	N	P_2O_5	K_2O	CaO
Representative mineral soil	5.00	95.0	.25	.15	1.80	.70
Minnesota peat [1]	94.00	6.0	1.70	.16	.04	.31
Minnesota peat [1]	59.00	40.3	2.35	.36	.17	2.52
Minnesota Muck [1]	50.6	49.4	1.92	.40	—	—
Minnesota Muck [1]	41.4	58.6	1.78	.21	—	—
Florida peat [2]	68.4	31.6	2.63	.20	.17	—
Canadian peat [3]	74.3	25.7	2.19	.20	.16	—
German peat [4] (Low lime)	97.0	3.0	1.20	.10	.05	.35
German peat [4] (High lime)	90.0	10.0	2.50	.25	.10	4.00

phosphorous and, especially, potash. It is also a good practice to start vigorous decay by the applicaton of barnyard manure, as the nitrogen carried by muck soils is usually not very readily available to plants.[5]

[1] Alway, F. J., *Agricultural Value and Reclamation of Minnesota Peat Soils;* Minn. Agr. Exp. Sta., Bul. 188, Mar., 1920.

[2] Pickel, G. M., *Muck: Composition and Utilization;* Fla. Agr. Exp. Sta., Bul. 13, 1891.

[3] Rept. Can. Exp. Farms, 1910. Rept. of chemist, p. 160.

[4] Fleischer, M., *Die Anlage und die Bewirtschaftung von Moorwiesen und Moorweiden;* Berlin, 1913.

[5] Publications regarding the practical utilization of peat and muck lands: Robinson, C. S., *Utilization of Muck Lands;* Mich. Agr. Exp. Sta., Bul. 273. 1914. Whitson, A. R., *et al., The Improvement of Marsh Soils;* Wis. Agr. Exp. Sta., Bul. 205. 1914. Stevenson, W. H., and Brown, P. E., *Improving Iowa's Peat and Alkali Soils;* Ia. Agr. Exp. Sta., Bul. 157. 1915. Smalley, H. R., *Management of Muck Land Farms in Northern Indiana and Southern Michigan;* U. S. Dept. Agr., Farmers' Bul. 761. 1916. Thompson, H. C., *Truck Growing on Peat Soils;* Jour. Amer. Peat Soc., Vol. II, No. 3, pp. 113-125. 1918. Alway, F. J., *Agricultural Value and Reclamation of Minnesota Peat Soils;* Minn. Agr. Exp. Sta., Bul. 188. Mar., 1920.

In many cases muck and peat are underlaid at varying depths by a soft impure calcium carbonate, called bog-lime.[1] Such a deposit may come from the shells of certain of the Mollusca, which have inhabited the basin, or from aquatic plants, such as mosses, algæ and species of Chara. In carbonated water these plants become incrusted with calcium carbonate, possibly because of their ability to absorb carbon dioxide,[2] thus precipitating the carbonate. In most cases this carbonate accumulation is due to a combination of the two agencies. Such material, because of its richness in calcium, is valuable as a soil amendment, and often, where it is found pure enough in quality and in sufficiently large quantities, it is handled commercially.

27. Colluvial soils.—This soil is formed in regions of precipitous topography, and is made up of fragments of rocks detached from the heights above and carried down the slopes by gravity. Talus slopes, cliff debris, and other heterogeneous rock detritus are examples of colluvial soil. Avalanches are made up largely of such material.

As the physical forces of weathering are most active in the formation of these soils the amount of solution and oxidation is usually small. The upper part of the accumulation exhibits physical action to the greatest extent, the particles being angular, coarse, and comparatively fresh; farther down the slope the material may merge by degrees into ordinary soil.[3] Such soils are usually shallow and stony, and approach the original rock in color unless large amounts of organic matter have accumulated. Colluvial soils are not of great importance

[1] Bog-lime is often spoken of as marl. Marl, as used by the geologist, refers to a calcareous clay of variable composition. Bog-lime, when it contains numerous shells, is often termed shell-marl. See Stewart, C. F., *The Definition of Marl;* Econ. Geol., Vol. 4, No. 5, pp. 485-489, 1909.

[2] $CaH_2(CO_3)_2 \rightleftharpoons CO_2 + H_2O + CaCO_3$.

[3] Colluvial soils generally merge so gradually into alluvial fans that the line of separation is difficult to establish. When the area of colluvial material is small, as it usually is, it is best included in the fan soils.

agriculturally because of their small area, their inaccessibility, and their unfavorable physical and chemical characteristics.

28. Alluvial soils.[1]—In considering water as a soil-forming agency, it was found to have both cutting and transporting powers. Alluvial soils are the direct result of these activities, especially the latter. The carrying power of water varies directly as the sixth power of the velocity; so that doubling the velocity increases the transportive ability sixty-four times. Obviously any checking of a stream's velocity will force it to deposit its load, the larger particles first and the finer as the current becomes more sluggish. With changes of velocity different grades of material are laid down, giving rise to stratification, one of the important characteristics of an alluvial soil. Streams never deposit, either along their course or at their delta, all of their sediment. Many tons of material both in suspension and in solution are discharged yearly into the ocean.[2]

There are three general classes of alluvial soils: (1) flood plain deposits, (2) deltas, and (3) alluvial fans. As the outlet of a stream is approached, its gradient generally becomes less inclined and its current is slackened. In a large stream this often means an aggrading of the channel due to the deposited material. A stream on a gently inclined bed usually begins to swing from side to side in long, gentle curves, depositing alluvial material on the inside of the curves and cutting on the opposite banks. This results in oxbows and

[1] If a detailed discussion regarding alluvial, marine, and glacial activities is desired, the following books will be helpful: Tarr, R. S., and Martin, L. M., *College Physiography;* New York, 1918. Pirsson, L. V., *A Text Book of Geology,* Part I; New York, 1915. Emerson, H. L., *Agricultural Geology;* New York, 1920. The considerations of river and stream action by Russell and Davis are classical: Russell, I. C., *Rivers of North America;* New York, 1898. Davis, W. M., *The Rivers and Valleys of Pennsylvania;* Geological Essays, Boston, 1909.

[2] Streams each year discharge into the ocean, on the average, 100 tons of soluble matter for every square mile of drainage area. The Mississippi River pours into the Gulf of Mexico each year 406,250,000 tons of sediment, not to mention a vast amount of soluble salts.

lagoons, which are ideal not only for the further deposition of alluvial matter but also for the formation of cumulose soils. This state of meander naturally increases the probability of overflow in high water, a time when the stream is carrying much suspended matter. This suspended material is deposited over the flooded areas; the coarser near the channel, building up natural levees; the finer sediment farther away in the lagoons and slack water.

Due to a change in grade, a stream may cut down through its already well-formed alluvial deposits, leaving terraces on one or both sides. Often two, or even three, terraces may be detected along a valley, marking a time when the stream-bed was at these elevations. On the lower slopes of hills bordering valleys the colluvial deposits may touch or even mingle with the alluvial, furnishing the stream with some detritus. Flood plain soils are variable in character, ranging from sandy loams to heavy clays.

A great deal of the sediment carried by streams is not deposited in the flood plain but is discharged into the body of water to which the stream is tributary. Unless there is sufficient current and wave action the suspended material accumulates, forming a delta. Such deposits are by no means universal, being found at the mouths of but a small proportion of the rivers of the world. A delta is generally a continuation of the flood plain and as it is built farther and farther out the stream is forced to aggrade its bed and both flood plain and delta are raised. Near the front of the delta the land is swampy; farther back it is higher and may assume considerable agricultural importance.

Where streams descend from mountains or plateaus, sudden changes in gradient often occur as the stream emerges in the lower lands. A deposition of sediment is thereby forced, giving rise to alluvial fans.[1] They differ from deltas in their

[1] As already noted, alluvial fans and colluvial material are very closely related. Soil survey classifications usually do not recognize the latter separation.

location and in the character of their material. The material of the latter is generally sandy, more or less porous and well drained. Deltas, on the other hand, are characterized by poor drainage and by heavy soils, silt loams, clay loams and clays predominating.

FIG. 10.—The flood-plain and delta of the lower Mississippi River.

Alluvial soils, especially those of flood plain origin, are comparatively young. Delta and first bottom soils are usually in need of drainage. Alluvial fans and terrace soils are often loose and open to the point of droughtiness. The latter group is usually not so well supplied with organic matter as are the delta and flood plain soils, which exist under conditions where organic accumulation is rapid. All alluvial soils are greatly influenced by the source of the detritus. For example, a red upland soil will give a reddish alluvial, while a soil or rock poor in lime will certainly not be parent to one rich in that constituent. Alluvial soils are generally richer in the essential constituents than the soils from which they are a wash, as is shown by the following data from North Carolina.

Table VII

CHEMICAL ANALYSES OF TWO ALLUVIAL SURFACE SOILS AND THE RESPECTIVE SURFACE SOILS FROM WHICH THEY WERE DERIVED.[1]

Constituents	1 Alluvial	2 Upland	3 Alluvial	4 Upland
N	.073	.048	.173	.038
P_2O_5	.076	.041	.118	.027
K_2O	1.697	1.330	.433	.286
CaO	1.103	.200	.417	.221

Delta soils, where they occur in any acreage, are very important. The deltas of the Mississippi, Ganges, Po, Tigris, and Euphrates rivers are striking examples. Egypt, for centuries the granary of Rome, bespeaks the fertility of such land. Flood plain soils are found to a certain extent along every stream, the greatest development in the United States occurring along the Mississippi. This area varies from forty to sixty miles in width and has a length from Cairo to the Gulf of over 600 miles. Such soils are very rich but, if they are first bottoms, they require drainage and protection from overflow. Alluvial fan soils are found over wide areas in arid and semi-arid regions and when irrigated and properly handled have proven very productive. They often occur in large enough areas in humid regions to be of considerable

[1] Williams, C. B., *et al., Report on the Piedmont Soils;* Bul. N. C. Dept. Agr., Vol. 36, No. 2, Feb., 1915.

1. Average of 8 analyses of Piedmont alluvial soils, Congaree series, to a large extent a wash from the Cecil.
2. Average of 71 analyses of Cecil series soils, the typical upland soil of the North Carolina Piedmont.

Williams, C. B., *et al., Report on the Coastal Plain Soils;* Bul. N. C. Dept. Agr., Vol. 39, No. 5, May, 1918.

3. Average of 8 analyses of coastal plain alluvial soils, Johnston and Kalmia series.
4. Average of 165 analyses of Norfolk series soils, the typical upland coastal plain soil of North Carolina.

importance. The type of farming and the crops grown on any area of alluvial soil will vary with climate, soil conditions, and markets.

29. Marine soils.[1]—A great deal of the sediment carried away by stream action is eventually deposited in the sea, the coarser fragments near the shore, the finer particles at a distance. Such material is largely clastic and if there have

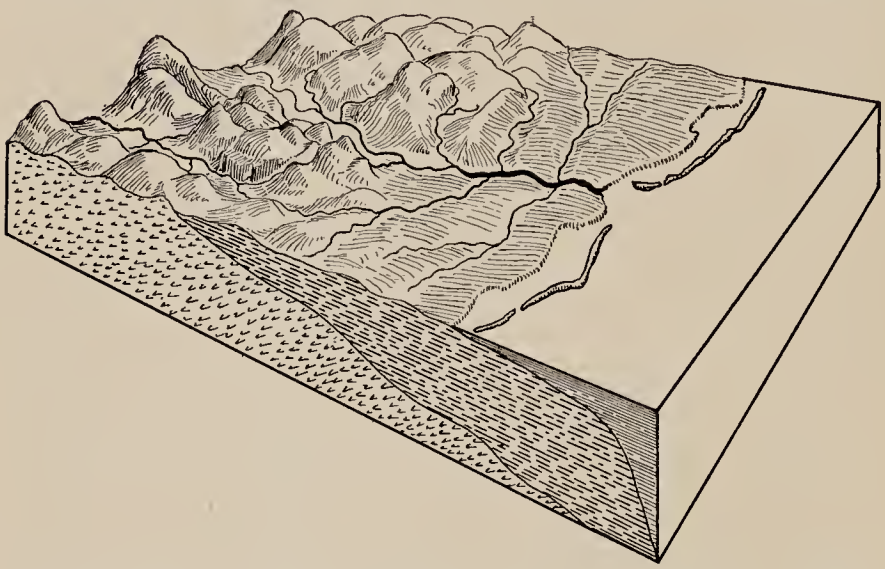


FIG. 11.—Block diagram showing how marine soils are formed and their relation to the uplands. The emerged coastal plain has already suffered some dissection from stream action. (After Emerson.)

been many changes in shorelines, the alternating beds will show no regular sequence. Such material, when raised above the sea by diatrophism and subjected to sufficient weathering and denudation, is classed as marine soil. (See Fig. 11.)

Such material has been worn and triturated by a number of agencies. First, the forces necessary to throw it into stream suspension were active, and next it was swept into

[1] For an excellent discussion of the marine soils of the Atlantic and Gulf coasts of the United States see Bennett, H. H., *Soils and Agriculture of the Southern States;* New York, 1921.

the ocean to be deposited and stratified, possibly after being pounded and eroded by the waves for years. At last came the emergence above the sea and the action of the forces of weathering *in situ*. The latter effects are of great moment since they determine not only the topography but the fertility of the new soil as well. The availability of the nutritive elements, and especially the amounts of organic matter, are determined by recent and still active forces.

The marine soils of the United States, while younger than most of our residual soils, are usually more worn and generally carry less of the nutrient elements. Their silica content is very high and they are often sandy, especially along the Atlantic seaboard. Sands, sandy loams, and loams predominate, although silt loams and clays are by no means unusual, especially in the Atlantic and Gulf coastal flatwoods and the black prairies and interior flatwoods of Alabama and Mississippi. The organic content of the sandy soils is generally low, but on the heavier types it may almost equal delta and flood plain soils.

A direct comparison [1] between typical coastal plain and residual soils usually shows the former to be considerably higher in silica but lower in iron and aluminium. The marine soil is, on the other hand, lower in phosphoric acid and potash. The nitrogen, organic matter, and lime are so variable in both soils that no reliable deductions can be drawn. The following data from Eastern United States substantiate the above generalizations.[2] (Tables VIII and IX, page 52.)

The soils of the Atlantic and Gulf coastal provinces, formed as vast outwash plains and occupying 11 per cent. of the area of the United States, are very diversified, due to source of

[1] When soils are compared on the strictly chemical basis great caution should be observed in drawing conclusions as to relative productivity. The amount of a nutrient present is by no means a measure of its availability. A chemical analysis usually throws but little light on the fertilizer needs of a soil.

[2] See also Walker, S. S., *Chemical Composition of Some Louisiana Soils as to Series and Texture;* La. Agr. Exp. Sta., Bul. 177, Aug., 1920.

Table VIII

COMPARATIVE COMPOSITIONS OF COASTAL PLAIN AND RESIDUAL SOILS OF EASTERN UNITED STATES.[1]

Constituents	1 Costal Plain	2 Residual
SiO_2	93.44	77.72
TiO_2	.69	.90
Al_2O_3	1.96	9.13
Fe_2O_3	1.17	3.75

Table IX

COMPARATIVE COMPOSITIONS OF NORTH CAROLINA COASTAL PLAIN AND RESIDUAL SOILS.[2]

Constituents	1 Costal Plain	2 Coastal Plain	3 Residual
N	.038	.138	.048
P_2O_5	.027	.033	.041
K_2O	.286	.346	1.330
CaO	.221	.394	.200

[1] Robinson, W. O., *et al., Variation in the Chemical Composition of Soils;* U. S. Dept. Agr., Bul. 551, June, 1917.

1 and 2. Average analyses of 15 coastal plain and 8 residual soils, respectively, taken from various places in eastern United States.

[2] Williams, C. B., *et al., Report on the Coastal Plain Soils;* Bul. N. C. Dept. of Agr., Vol. 39, No. 50, May, 1918.

1. Average of 165 analyses of Norfolk series soils. This is the typical soil of the Atlantic coastal plain.
2. Average of 84 analyses of Portsmouth series soils. This series is above the average coastal plain soil in organic matter and fertility.

Williams, C. B., *et al., Report on the Piedmont Soils;* Bul. N. C. Dept. of Agr., Vol. 36, No. 2, Feb., 1915.

3. Average of 71 analyses of Cecil series soils. This series is the typical residual soil of the Piedmont plateau.

material, age, and climatic conditions. There are great tracts of general farming land, besides wide areas of special-purpose soils adapted to highly specialized industries. The latter soils require refined and intensive methods of cultivation. Except for certain areas the coastal plain soils are well aërated and easy to cultivate. Except in the lower coastal plain belt they are well drained. Severe leaching as well as serious erosion occurs in times of heavy rainfall. When sufficiently supplied with organic matter, carefully fertilized, and cultivated properly, these soils support a great variety of crops such as cotton, maize, oats, forage crops, and peanuts, besides vegetables and fruits of many varieties.

30. The ice age and the American ice sheet.[1]—If in any region the temperature and snowfall stand in such relationship that the heat of summer does not offset the winter's accumulation of snow, great snowfields form. If this condition persists year after year the temperature is reduced to such an extent as to increase the proportion of the snowfall, which escapes the summer heat. The pressure of overlying snow and the influence of the summer melting soon change the snow into ice with a complicated recrystallization. As the depth of the accumulation increases outward movement is inaugurated due to the strong lateral pressure. As the ice moves slowly forward under this tremendous pressure, with an almost incredible thickness and a plasticity which ordinary ice does not possess, it conforms itself to the unevenness of the areas invaded. It rises over hills and shapes itself to valleys with surprising ease. Not only is the existing soil mantle swept away by such an invasion but the underlying rocks are ground and gouged. When the ice melts back and the region is again free a mantle of soil material remains.

[1] For a complete discussion of glaciers and glaciation, see Salisbury, R. D., *The Glacial Geology of New Jersey;* Geol. Survey of New Jersey, Vol. 5, 1902.

This drift is often merely ground-up rock, at other times the original soil is mixed with foreign detritus, while again the variable mixtures may be wholly reworked and considerably stratified. Besides this the streams of water, which issue from under the ice, may be instrumental in distributing sediments for miles beyond the ice front. Glacial lakes, when in existence for sufficiently long periods, furnish basins for the deposition of materials derived from the erosive and grinding influence of the ice. The ice may also provide a large amount of detritus so fine as to be susceptible to wind movement, and thus æolian influences as well as alluvial and lacustrine may be concomitant to a great ice invasion.

During the Pleistocene northern North America, as well as part of Europe, was successively invaded by ice sheets, which exerted the influences above described and, while the central ice caps in Canada probably never wholly disappeared, the regions to the southward certainly experienced alternate glaciation and interglaciation. At least five invasions are evident in central United States. Debris from the last, called the Wisconsin, now covers wide areas. The interglacial periods are shown by forest beds, accumulations of organic matter, and evidences of erosion between the drift deposited by the successive ice sheets. Some of the interglacial periods evidently were times of warm, and even semitropical, climate. Just what was the exact cause of the ice age is still under dispute.[1] That it was due to a change in the carbon dioxide content of the air seems as probable as any of the numerous hypotheses that have been advanced.

The area covered by glaciers in North America is estimated as 4,000,000 square miles, while at least 20 per cent. of the United States is either directly or indirectly influenced by the debris. The greatest southward extension of the ice is marked

[1] Humphreys, W. J., *Factors of Climatic Control,* Jour. Franklin Inst., Vol. 189, No. 1, pp. 63-98, Jan., 1920.

by a terminal moraine wherever the ice margin was stationary long enough to permit such an accumulation. Many other moraines are found to the northward, marking points where the ice became stationary for a time as it retreated by melting.[1] While the moraines are generally outstanding topographic features, they are commonly unimportant agriculturally due to their small area and unfavorable physiography. The ground moraine is the material which furnishes the bulk of the soils which have directly resulted from glaciation. This ground moraine is of wide extent and possesses a favorable agricultural topography. The weathering *in situ* of this great area of soil material has evolved one of the most productive soil provinces of the world.

31. Glacial soils.—The soils which have been developed from the glacial till are usually rather heavy, loams, silt loams, and clay loams predominating. The subsoil is generally finer than the surface and may induce poor drainage. The individual particles of such soils are less weathered than those of residual soils. The feldspars have retained their normal luster and the iron staining so common in the Piedmont Plateau is almost absent. The color is usually subdued, grays and browns prevailing. Red glacial soil may occur, however, where red sandstones have been ground up or where considerable residual soil has been incorporated in the till. The subsoils usually present colors ranging from light gray and yellows to brown. Mottling is common, especially in the subsoil, due to lack of aëration.

The chemical composition of glacial soils approaches that of the parent rock more nearly than does any other, since

[1] The position of the ice front of a glacier is determined by the relationship between the forward movement of the ice and the rate of melting. When the former is dominant, the ice front advances. When melting in dominant, the ice front recedes. When these two forces are balanced, conditions are favorable for a stand of the ice and the building of a moraine.

the forces of weathering, while they have had time to produce a soil from the material left by the ice, have not as yet seriously depleted the essential constituents. The mineral elements in such soils are governed to a considerable degree by the composition of the original rock. Calcium content,

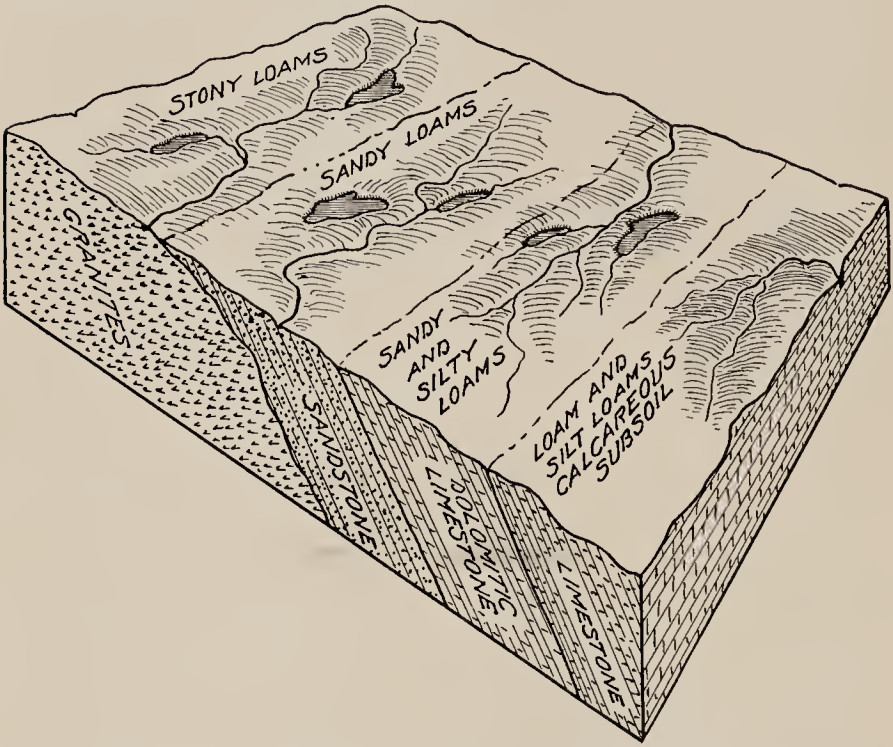


FIG. 12.—Block diagram showing the relationship which sometimes exists between glacial soils and the underlying rocks. Glacial movement left to right. (After Emerson.)

for example, is controlled largely by such a relationship. The hill soils of southern New York (Volusia and Lordstown) come from shales low in lime and their productiveness is seriously affected thereby. On the other hand, certain glacial soils of central New York and of the Mississippi Valley (Ontario and Miami) have been formed from calcareous till and owe their productivity partly thereto. Gla-

cial soils from limestones generally contain plenty of lime, a condition that is far from true with residual soils.[1]

The organic content of glacial soils depends to a large extent on the climatic conditions under which the soil has existed since its formation. If environmental factors have been such as to encourage the accumulation of organic matter, these soils will exhibit the deep black color that arises from the presence of such material. If, however, conditions do not encourage the natural growth of a heavy vegetation, the amount of organic matter in such virgin soil will be low. Lime and other nutritive elements may also be a great factor in the development of vegetation on these soils. Glacial till soils are distributed over all the area north of the great terminal moraine, and stretch, roughly, from New England to the Pacific coast. They comprise a great variety of soils, differing not only in their physical characters, but also as to fertility. They are adapted to many crops, but general farming is practiced on them to the greatest degree. This means extensive, rather than intensive, operations. In some

[1] Partial Analyses of Soils from the Limestone Driftless and Glacial Region of Wisconsin [2] Are of Interest in This Regard:

Constituents	Residual		Glacial	
	1	2	3	4
SiO_2	71.13	49.13	40.22	48.81
$Al_2O_3 + Fe_2O_3$	18.02	31.12	11.30	10.07
MgO	.38	1.92	7.80	7.95
CaO	.85	1.22	15.65	11.83
K_2O	1.61	1.61	2.36	2.60
P_2O_5	.02	.04	.05	.13
CO_2	.43	.39	18.76	15.47

[2] Chamberlain, T. C. and Salisbury, R. D., *The Driftless Area of the Upper Mississippi;* Sixth Ann. Rep. U. S. Geol. Survey, pp. 249-250, 1885. These analyses illustrate to very good advantage the beliefs entertained by Chamberlain and Salisbury regarding the differences between residual and glacial clays. Residual clay is designated by them as "rock rot," and glacial clay as "rock flour." The latter, being less weathered, retains a larger proportion of its easily soluble materials.

regions dairying has been developed to a large extent, while in certain localities, where climate, soil, and market are favorable, trucking is of great importance.

32. Effect of glaciation on agriculture.[1]—In comparing glaciated soils with corresponding residual areas, certain differences are usually apparent. The agricultural condition within the zone of glaciation is usually consistently higher than that beyond the regions of drift accumulation. The extensive leveling due to glacial erosion and deposition has almost always resulted favorably for agricultural operations. Even the thickness of the drift is found to conserve the ground water supply. While it is difficult to show any consistent difference between residual and glacial soils as to total constituents, it is generally admitted that glaciation has been a benefit to agriculture, in that the soils have been rejuvenated and their crop-producing power raised.

The dominant textural quality of glacial soils seems adapted to certain staple food crops, and, due to their intermingling, a considerable opportunity for diversified and intensified farming is offered. It is, therefore, evident that in any study of soils, particularly those of the United States, a careful consideration of the effects of glaciation is necessary. Even the alterations in topography are factors not to be ignored. In a comparison of the driftless area of Wisconsin with the glaciated parts only 43 per cent. of the former is improved as against 61 per cent. of the latter, while the value of the farms on the glaciated soil averages 50 per cent higher. The same general differences appear between the glacial and residual soils of Indiana and Ohio.

33. Lacustrine soils—glacial lake.—Great torrents of water were constantly gushing from the front of the great

[1] Whitbeck, R. H., *The Glaciated and Driftless Portions of Wisconsin;* Bul. Geog. Soc. Phil., Vol. IX, No. 3, pp. 10-20, 1911. Von Englen, O. D., *Effects of Continental Glaciation on Agriculture;* Bul. Amer. Geog. Soc., Vol. XLVI, pp. 353-355, 1914. Ames, J. W., and Gaither, E. W., *Soil Investigations;* Ohio Agr. Exp. Sta., Bul. 261, 1913.

ice sheets as they advanced and retreated in response to their environment. The great loads of sediment carried by such streams were either dumped down immediately or carried to other areas for deposition. As long as the water had ready egress it flowed rapidly away to deposit its load as gravelly

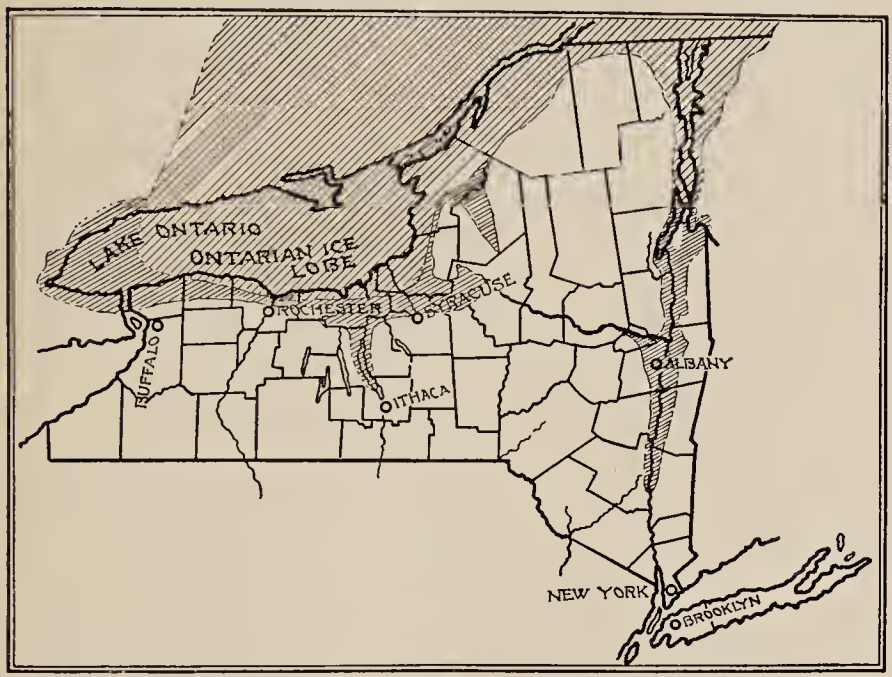


FIG. 13.—Diagram showing how glacial lakes were formed in New York State. The lighter shading represents the Ontarian ice lobe; the darker shading indicates the position of the glacial lake waters in the Ontario and Hudson river basins. (After Fairchild.)

outwash, river terraces, valley trains and alluvial fans. In many cases, however, the ice front came to a stand where there was no such ready egress and ponding occurred. Often very large lakes were formed which existed for many years. (See Fig. 13.)

With the ice melting rapidly on the hill tops these lakes were constantly fed by torrents from above, which were laden with sediment derived not only from under the ice,

but also from the unconsolidated till sheet over which it flowed. As a consequence there were in the glacial lakes deposits ranging from coarse delta materials near the shore to fine silts and clay in the deeper and stiller waters. Such materials now cover large areas, not only in New York state and along the Great Lakes, but also in the Red River Valley and in the valleys of the Rocky Mountains and the Cascades and Sierra Nevadas. They make up by far the most important of the lacustrine soils. Glacial lake soils probably present as wide a variation in physical characteristics as any of the great soil provinces. Being deposited by water they have been subject to much sorting and stratification, and range from coarse gravels on the one hand to fine clays on the other. They are generally found as the lowland soils in any region, although they may occur well up on the hillsides if the shores of the old lakes encroached thus far. The color of such soils varies from gray to black, according to the degree of organic matter present. The organic content of such soils, as with the glacial till, varies with climate, and may be high, low, or medium according to conditions. The thickness of glacial lake deposits is variable, ranging from a few to many feet. In chemical composition they closely approximate the soil material from which they were derived. This is particularly true as regards the presence of lime. The distribution of glacial lake deposits is not only wide but the areas are large enough to be of great agricultural influence. Extending westward from New England along the Great Lakes until the broad expanse of the Red River Valley is reached these deposits have produced some of the most important soils of the northern states. They are valuable not only for extensive cropping with grain and hay, but also for fruit and trucking.

34. Lacustrine soils—recent lake.—While the glacial lake deposits were formed many thousands of years ago the lake soils of the second group are still in process of construc-

tion. It is a well-known fact that lakes are only enlarged stream beds, and are doomed ultimately to be filled by river sediments. Such soils have been reclaimed to a certain extent, but their acreage is not large enough to give them the importance of the glacial lake soils. The lake soil is usually of a fine character, rich in organic matter and of good tilth. If properly drained, it is almost invariably highly productive, and is adapted to a variety of crops depending on climatic conditions.

35. Æolian soils.—Loess.—During glaciation much fine material was carried miles below the front of the ice sheets by streams that found their source within the glaciers. This fine sediment was deposited over wide areas by the overloaded rivers. The accumulations occurred below the ice front at all points, but seem to have reached their greatest development in what is now the Missouri Valley and the Great Plains. Much of the sediment in the latter area probably came from local glaciers, which debouched from the Rockies.

It is generally agreed by glacialists, that a period of aridity, at least as far as this particular region is concerned, immediately followed the retreat of the ice. The low rainfall of this period was accompanied by strong westerly winds. These winds, active perhaps through centuries, were instrumental in the picking-up and distributing of this fine material over wide areas of the Mississippi, Ohio, and Missouri valleys. One strong argument for this æolian origin is that the soil is in its deepest and most characteristic development along the eastern banks of the large streams. Especially noticeable is the extension down the eastern side of the Mississippi River almost to the Gulf of Mexico. This wind-blown material, called loess, is found over wide areas in the United States, in most cases covering the original till mantle. It covers eastern Nebraska and Kansas, southern and central Iowa and Illinois, northern Missouri and parts of Ohio and

Indiana, besides a wide band, as already noted, extending southward along the eastern border of the Mississippi River. Due to its mode of origin, its depth is always greatest near the streams and gradually becomes less farther inland. In places, notably along the Missouri and Mississippi rivers, its accumulation has given rise to great bluffs, which bestow a characteristic topography to the region.

Not only is loess found over thousands of square miles in the central part of the United States but it occurs elsewhere in large areas. It is greatly developed in northern France and Belgium, and along the Rhine in Germany, where it is an important soil in all the valleys that are tributary to that river. Silesia, Poland, southern Russia, Bohemia, Hungary and Roumania have deposits of this highly fertile material. Some of the most important moves of the World War had as their aim the possession of these fertile areas. In China loess is found over a very large part of the valley of the Hwangho, a region probably larger in area than France and Germany combined. The thickness of the deposit is variable, ranging from a few feet to several thousand in places. The depth is practically always sufficient for any form of agricultural operations.

Loess is usually a fine calcareous silt or clay loam, of a yellowish or yellowishy buff color. While it may be readily pulverized when subjected to cultivation, it possesses remarkable tenacity in resisting ordinary weathering. The vertical walls and escarpments formed by this soil show one of its striking physical characteristics. In China caves that house thousands of persons are dug in the defiles and canons existing in this deposit. Another feature of loess is the presence, especially in the subsoil, of minute vertical canals lined with a deposit of calcium carbonate. These canals are supposed to give the soil its vertical cleavage and its tenacity. The particles of loess are usually unweathered and angular. Quartz seems to predominate, but large quantities of feld-

spar, mica, hornblende, augite, calcite and other minerals are found.

A few typical analyses are given below which show the variability that may be expected, especially in the nitrogen, phosphoric acid, potash, and lime.

TABLE X

ANALYSES OF AMERICAN LOESS SURFACE SOILS[1]

CONSTITUENTS	1	2	3	4
SiO_2.....	71.30	81.13	86.96	69.66
TiO_2.....	.60	.78	.69	1.72
Al_2O_3.....	11.47	8.52	4.69	12.71
Fe_2O_3.....	4.05	2.92	2.86	4.89
MgO.....	1.10	.39	.43	1.28
CaO.....	1.38	.31	.71	1.09
Na_2O.....	1.95	.52	1.07	1.17
K_2O.....	2.40	1.78	.91	2.42
P_2O_5.....	.23	.08	.07	.15
N.....	.22	.11	.11	.23

Whenever moisture relations are favorable, loess is an exceedingly fertile soil. Under heavy cropping, especially when little in the way of organic or mineral matter is returned, this soil shows a need of phosphoric acid and lime, the application of which is becoming part of good farm practice in the Central West. Considering the wide extension of

[1] 1. Marshall silt loam, Pottawattamie Co., Ia.
Bennett, H. H., *Soils and Agriculture of the Southern States*, p. 332; New York, 1921.

2. Memphis silt loam, Grenada Co., Miss.
Robinson, W. O., *et al.*, *Variation in the Chemical Composition of Soils;* U. S. Dept. Agr., Bul. 551, June, 1917.

3. Cherokee silt loam, Cherokee Co., Kan.
Bennett, H. H., *Soils and Agriculture of the Southern States*, p. 332; New York, 1921.

4. Silt loam, Weeping Water, Neb.
Alway, F. J., and Rost, C. O., *The Loess Soils of the Nebraska Portion of the Transition Region*, Part IV; Soil Sci., Vol. I, No. 5, p. 431, May 1916.

the loess and the great variety of climate and cropping to which it is subject, it may be classed as one of the world's most important soils. In the United States it is the great maize-producing soil of the upper Mississippi Valley.

36. Other æolian soils.—The term "adobe" is applied to a fine calcareous clay or silt formed in a manner somewhat like loess. It is supposed that, while part of the deposit came from the waste of talus slopes as mountains were weathered under conditions of aridity, the remainder had æolian origin. Certain characteristics also seem to indicate that the valley adobe might have been deposited almost entirely by water. It appears, therefore, that, while the physical characteristics of all adobe are somewhat similar, its mode of origin and chemical composition may be variable.

Like the loess, the adobe is an exceedingly rich soil, but it occurs in an arid or a semi-arid region. When irrigated its fertility seems inexhaustible. It is found in Colorado, Utah, southern California, Arizona, New Mexico, and Texas. It has an especially wide distribution in New Mexico. Like loess, its elevation is variable, ranging from sea level in California and Arizona to 6000 feet along the eastern border of the Rocky Mountains. Its maximum thickness cannot be estimated, as it is very little eroded and is supposed to be still accumulating. Some valleys are known to be filled to a depth of 3000 feet with this material. Its characteristics are its fine texture, its great depth, its wide distribution, and its great fertility when moisture conditions are suitable for crop growth.

Sand dunes are the outgrowth of two conditions—a large quantity of sand and a wind that blows in a more or less prevailing direction. Under such conditions the sand and other fine materials are not only blown into heaps, but also tend to move in the direction of the prevailing wind. Sand dunes may often assume gigantic proportions, sometimes being several hundred feet high and twenty or thirty miles

long. In such proportions they become a grave menace to agriculture, not only because they are an absolutely valueless medium for plant growth, but also because they cover fertile lands and entirely blot out all vegetation.

From early geologic times deposits of the very fine material, that is continually being ejected from volcanoes, have been distributed over the earth's surface. These deposits are usually flour-like, and while at one time they probably covered many square miles of territory, they have succumbed very largely to erosion and denudation, and only remnants are found at the present time. Such material may be found in Montana, Nebraska, and Kansas. Æolian deposits of this character are usually rather porous and light, and are likely to be highly siliceous. They are not of great agricultural importance, except in certain localities.

37. Resume.—The geological classification of soils provides a logical basis for the discussion of the formation, character, and agricultural value of soils in general. A detailed consideration on any other basis would lead to endless confusion and repetition. In classifying soils a study must be made not only of the past effects but of the present influences of the soil-forming processes, and while the conclusions and observations are apparently purely agricultural in nature, they really spring from a geochemical foundation.

With such a classification at hand one cannot fail to understand the occurrence of so many distinct and different types of soil. It is really difficult to see why soils do not present greater differences and why transition types do not utterly prevent clean-cut field distinctions. In such soil study the all-important character of climatic control must always be remembered. Weathering is strictly a climatic influence and crop adaptation is usually dominated by climate rather than by soil.

CHAPTER IV

THE SOIL PARTICLE AND CERTAIN IMPORTANT RELATIONS

An examination of a soil, however cursory, immediately reveals that it is made up of irregular fragments of mineral material mixed and more or less coated with organic matter. These fragments, varying in size from particles easily discernible by the naked eye to particles so fine as to be invisible under the ultra-microscope, determine to a very large degree the complex relationships of soil to plant. The movement of air in the soil, the circulation of the water, chemical reactions resulting in solution, and the presence and virility of the various organisms are determined largely by the size of particles making up a soil and by the proportion and condition of the organic material present. In expressing the size or sizes of particles making up a soil, the term *texture* is used. Thus a soil texture may be coarse, medium, or fine, indicating that the particles making up the soil conform in general to such description.

Texture is a condition which can be but little modified in a normal soil. We have seen how a rock can be disintegrated, decomposed and gradually built into a soil. A change in texture has been wrought, but such a process demands geologic ages for its fulfillment. In the time covered by the life of man, the necessary forces are not active enough to have this effect; consequently, as far as the farmer is concerned, the texture of the soil in his field is subject to but slight alteration. A sand remains a sand and a clay remains a clay, as far as practical considerations are concerned. Changes

in texture may be made on a small scale by mixing two soils, but this is not practicable in the field.

38. Separation and classification of soil particles.—In order that the particles of soil, varying so tremendously in size as they do, may be studied successfully, they must be separated into groups according to their diameters. The various groups are spoken of as soil separates. Such a grouping is of course arbitrary, and must meet certain theoretical as well as practical requirements. It must be simple, short, and capable of expressing in a practical way the physical character of the soil. Moreover, it must lend itself to the actual separation and percentage evaluation of each group. This analytical procedure is called a *mechanical analysis.*

With the large number of different methods of mechanical soil analyses, there has arisen considerable variation in textural groupings expressed in diameter of particles. This would naturally occur because of the differences in degree of refinement, which the various methods of separation allow, and also because of the uses which the investigators wished to

TABLE XI

THE NAMES AND RANGES IN SIZE OF SOIL PARTICLES AS ESTABLISHED BY THE BUREAU OF SOILS CLASSIFICATION[1]

SEPARATE	SIZE IN MILLIMETERS	FINE SANDY LOAM	CLAY
	m.m.	%	%
1. Fine Gravel....	2—1	1	1
2. Coarse Sand...	1—.5	2	2
3. Medium Sand..	.5—.25	3	2
4. Fine Sand.....	.25—.10	22	6
5. Very Fine Sand	.10—.05	35	7
6. Silt	.05—.005	27	39
7. Clay	.005 and below	10	43

[1] Briggs, L. J., *et al., The Centrifugal Method of Soil Analysis;* U. S. Dept. Agr., Bur. Soils, Bul. 24, 1904.

make of such analyses. The grouping established by the United States Bureau of Soils is met with in all soil literature and is really the standard classification for this country. Table XI sets forth the essential points of the Bureau of Soils classification. In the first column are given the names of the various separates, and in the second the range in size of each group. Columns three and four show the percentages of each separate in two very different specimen soils, a sandy loam and a clay. In order to obtain such figures, a sample of the dry soil must actually be separated into the arbitrary groups and the percentage of each group to the whole soil calculated from the dry weights obtained. This operation is the mechanical analysis already mentioned.

This classification establishes seven distinct groups[1] rang-

[1] VARIOUS TEXTURAL CLASSIFICATIONS OTHER THAN THAT OF THE BUREAU OF SOILS USED IN THE MECHANICAL ANALYSES OF SOILS. EXPRESSED IN DIAMETER OF PARTICLES IN MILLIMETERS

SEPARATE	OSBORNE[1]	HILGARD[2]	ENGLISH[3]	ATTERBERG[4]
1	3.00-1.00	3.00-1.00	1.00 - .200	20.00 -2.00
2	1.00- .50	1.00- .50	.20 - .040	2.00 - .20
3	.50- .25	.50- .30	.04 - .010	.20 - .02
4	.25- .05	.30- .16	.01 - .002	.02 - .002
5	.05- .01	.16- .12	.002- —	.002- —
6	.01- —	.12- .07 and six other divisions		

[1] Osborne, T. B., *Methods of Mechanical Soil Analysis;* Ann. Rep. Conn. Agr. Exp. Sta., 1886, pp. 141-158; 1887, pp. 144-162; 1888, pp. 154-157.

[2] Hilgard, E. W., *Methods of Physical and Chemical Soil Analysis;* Ann. Rep. Cal. Agr. Exp. Sta., 1891-1892, pp. 241-257.

[3] Hall, A. D. and Russell, E. J., *Soil Surveys and Soil Analysis;* Jour. Agr. Science, Vol. IV, part 2, pp. 182-223, 1911.

[4] Atterberg, A., *Die Mechanische Bodenanalyse und die Klassifikation der Mineralboden Schwedens.* Internat. Mitt. f. Bodenkunde, Band II, Heft 4, Seite 312-342, 1912. Schucht, F., *Über die Sitzung der Internationalen Kommission für die Mechanische und Physikalische Bodenuntersuchung in Berlin* am 31, October 1913; Internat. Mitt. f. Bodenkunde, Band IV, Heft I, Seite 1-31, 1914.

ing from fine gravel, readily visible to the naked eye, to the clay separate, the largest particle of which is .005 of a millimeter or .0002 of an inch in diameter. The stone and large gravel, while they figure in a practical examination and description of a soil in the field, obviously need not be considered in such a classification as this.

The seven separates may be thrown into two groups for a preliminary examination on the basis of visibility to the naked eye. The gravel and sand particles are readily seen, while the silt and especially the clay particles are invisible as individuals, although some of the larger silt particles may be seen with the naked eye when suspended in water. The gravel and sand, when dominant in a soil, give properties known to every one as *sandy,* while if the soil is made up largely of silt and clay, its plasticity and stickiness proclaim it as *clayey* in nature. The characteristics of the two soils of the above table may be read easily from their mechanical analyses. The classification, therefore, meets the criteria already established. It is simple, easy to remember, and is capable of expressing, to a certain extent at least, the dominant physical characters of soils. As will be shown below, it lends itself to the quantitative separation of a soil, the so-called mechanical analysis.

39. The beaker method of mechanical analysis.—When fragments of rock or soil are suspended in water they tend to sink slowly, and it is a well recognized fact that, other things being equal, the rate of settling depends on the size of the particle. As the particle is decreased in size its weight decreases faster than the surface exposed to the buoyant force of the water. As a consequence the rapidity with which the soil particles settle is more or less proportional to their size. The suspension of a sample of soil would, therefore, be the first step in mechanical separation by water; the second step would be subsidence and the withdrawal of each successive grade of particles as it slowly settled; the third step would

be the determination of the percentage of each grade, or group, of particles as based on the original sample. This is precisely what every method of mechanical analysis in which water is utilized aims to do, although the irregularity in the shape of the particles prevents to a certain extent a perfect separation. The apparatus and technique of the various methods employed are generally rather complicated.

One of the earliest and most useful methods to be perfected was the separation of the various grades of soil by simple subsidence in a column of still water. This is commonly spoken of as the Osborne beaker method.[1] The determination is very simple. The soil sample is first fully deflocculated and thrown into suspension, each particle functioning separately. Beakers are commonly used as containers, but any vessel that is relatively deep will do for the determination. The larger particles, gravel and sand, will of course settle first, and the finer silts and clays may be decanted off. As the sands carry finer particles down with them, the suspension and subsidence must be repeated a number of times. The sands are later dried and sieved into their respective groups. The silt and clay particles, thus decanted, may be separated from each other by subsidence as above described. The time necessary for such decantation as will leave in suspension only particles below a given size is determined by the examination of a drop of the suspension under a microscope fitted with an eyepiece micrometer. In this way the size of the particles decanted may be measured accurately. (See Fig. 14.)

The four steps in this method of separation are: deflocculation of the sample; separation by successive subsidence and decantation; evaporation to dryness of the separates and the sieving of the sands; and the weighing of the separates and the calculation of percentages based on the original dry sam-

[1] Osborne, T. B., *Methods of Mechanical Soil Analysis;* Ann. Rep. Conn. Agr. Exp. Sta., 1886, pp. 141-158; 1887, pp. 144-162; 1888, pp. 154-157.

ple. The method, however, is slow, as the time necessary for each subsidence of the finer particles is very great and the number of individual subsidences is large. As a consequence, it has been superseded by methods that utilize centrifugal force for the finer separations, while retaining gravity for removing the various grades of sand.

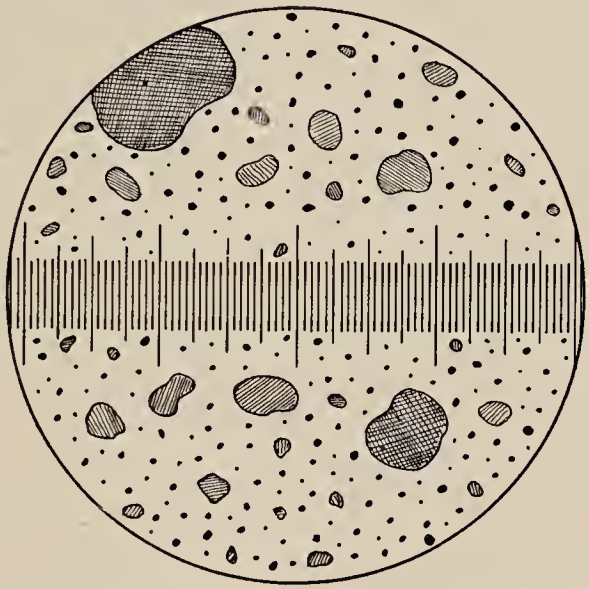


FIG. 14.—Diagram showing the relative sizes of soil particles as they appear under a microscope with eye-piece micrometer. Particles one space or less in diameter are clay; from one space to ten, silt and above ten spaces, very fine sand.

40. Bureau of Soils centrifugal analysis.—Of the centrifugal methods used in mechanical analysis that employed by the United States Bureau of Soils[1] is the most successful. A five-gram sample of well-pulverized soil is put into a shaker bottle of about 250 cubic centimeters capacity. This bottle is filled about two-thirds full of water so that in shaking the disintegrating force of the liquid may be utilized. A few

[1] Fletcher, C. C. and Bryan, H., *Modifications of the Method of Soil Analysis;* U. S. Dept. Agr., Bur. Soils, Bul. 84, 1912.

drops of ammonia are added to dissolve the organic matter and to make deflocculation easier. The sample is then agitated in the bottle until disintegration is complete. This period ranges from five to twenty hours, depending on the sample. (See Fig. 15.)

The separation of the silt and the clay from the sands is made in the shaker bottle by simple subsidence, the time for decantation being determined by a microscopic examination of a drop of the suspension. The silt and the clay are decanted directly into a test-tube fitted into a centrifuge. Whirling at the rate of 800 to 1000 revolutions a minute will cause the subsidence of the silt to the bottom of the test-tube in a few minutes. The clay is then decanted. The microscope is necessary here in order to determine when the settling of the silt is complete. As small particles tend to cling to the larger particles the entire operation must be repeated several times; therefore the processes of gravity subsidence and centrifugal subsidence are carried on side by side, material being constantly poured from the shaker bottle into the centrifuge tubes and from the test-tubes into the receptacles for the clay.

The centrifuge is usually large enough to allow the separation of several duplicate samples at once. The various separates made by this method are dried and weighed. The sands, which are obtained in bulk, are further separated by sieves into the grades desired. When a large quantity of organic matter is present it must be determined and included in the final report on the sample.

This method of mechanical analysis as perfected by the Bureau of Soils has been very commonly adopted by soil workers. It has many advantages over other methods.[1] In the first place, it is rapid, often requiring only hours where other

[1] Classification of the Various Methods of Mechanical Analysis:

1. *Sieve* { Wet or Dry } Used to separate sands in practically all methods.

methods take days for completion; secondly, it is simple, and the technique of the separation is easily acquired; thirdly, in the decantations no very large amount of water is accumulated with the separates, except for the clay, and thus the time and cost of evaporation is reduced. The clay, moreover, may be as accurately determined by difference as by direct methods, thus allowing a further saving of time. While the method is accurate only within one per cent., it is sufficiently precise for all practical purposes.

41. Physical characters of the soil separates.—It is immediately apparent that as these groups vary in size they must exhibit properties, especially physical ones, which are widely different. These properties should in turn be imparted to the soil of which the separates form a part. If a person is

2.	*Air*	——	(Cushman's[1] air elutriator).
3.	*Water*	In motion	Gravity (Schöne's[2] elutriator and Hilgard's[3] churn elutriator).
			Centrifugal (Yoder's[4] Centrifugal elutriator).
		At rest	Gravity (Osborne's beaker method and Atterberg's[5] modified silt cylinder).
			Centrifugal (Bureau of Soils method).

For a detailed discussion of all methods of mechanical analysis see Wiley, H. W., *Agricultural Analysis,* Vol. I, pp. 195-276; Easton, Pa., 1906.

[1] Cushman, A. S. and Hubbard, P., *Air Elutriation of Fine Powders;* Jour. Amer. Chem. Soc., Vol. 29, No. 4, pp. 589-597, 1907.

[2] Schöne, E., *Über Schlämmansalyse;* Bul. Soc. Imperiale des Naturalistes de Moscow, 40, Part 1, p. 324, 1867. *Über Schlämmanalyse und einen neuen Schlämmapparat;* Berlin, 1867. Also see Wiley, H. W., *Agricultural Analysis,* Vol. I, pp. 231-241; Easton, Pa., 1906.

[3] Hilgard, E. W., *Methods of Physical and Chemical Soil Analysis;* Ann. Rep. Calif. Agr. Exp. Sta., pp. 241-257, 1891-1892.

[4] Yoder, P. A., *A New Centrifugal Soil Elutriator;* Utah Agr. Exp. Sta., Bul. 89, 1904.

[5] Appiani, G., *Über einen Schlämmapparat fur die Analyse der Boden- und Thonarten;* Forsch. a.d. Gebiete d. Agri-Physik, Band 17, Seite 291-297, 1894. Atterberg, A., *Die Mechanische Bodenanalyse und die Klassifikation der Mineralboden Schwedens;* Internat. Mitt. f. Bodenkunde, Band II, Heft 4, Seite 312-342, 1912.

conversant with these various values, a mechanical analysis should reveal at a glance certain soil conditions, which may or may not be conductive to the best plant growth.

The sands and the gravel, because of their sizes, function as separate particles. They are irregular and rounded, the continual rubbing that they have received being sufficient in many cases to have effaced their angular character. They exhibit very low plasticity and cohesion, and as a consequence are little influenced by changes in water content. Their water-holding capacity is low, and because of the large size of the spaces between each separate particle the passage of percolating water is rapid. They, therefore, facilitate drainage and encourage good air movement. In all the grades of sand, the separate particles are visible to the naked eye, a condition impossible with the silt and clay groups. Soil containing much sand or gravel, therefore, is of open character, possessing good drainage and aëration, and is usually in a loose friable condition.

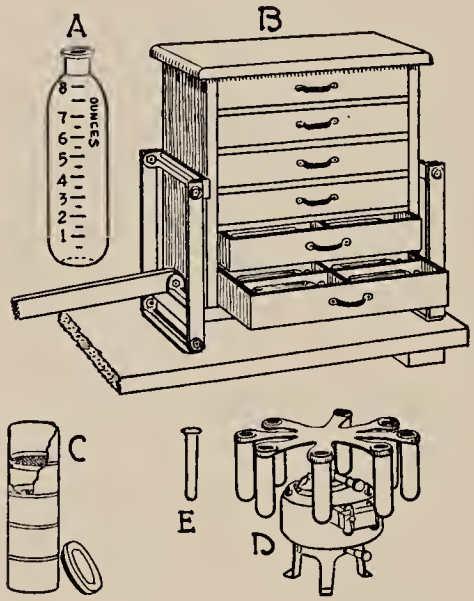


FIG. 15. — Apparatus for making a mechanical analysis of soils. Shaker-bottle (*A*), shaking-rack (*B*), sieves (*C*), centrifuge (*D*) and centrifuge-tube (*E*).

The clay and silt particles are very minute, many of the former being so small as to be invisible under the ultra-microscope. Both groups are really shreds and fragments of minerals often rather gelatinous in nature. The clay particles are highly plastic and when kneaded with just the correct

amount of water they become sticky and impervious. On drying, they shrink with the absorption of considerable heat. On wetting, again swelling occurs. The absorptive capacity of clay material for water, gases, and soluble salts is very high, due to the presence of colloidal material.[1] As material in a colloidal condition is very finely divided, it is found largely in the heavier types of soil. Some clays carry very large amounts of material in a colloidal state. Silt possesses the same properties of plasticity, cohesion, and absorption as does clay, but to a less extent, because the particles of the former are larger than those of the latter. The presence of silt and especially clay in soil imparts to it a heavy texture, with a tendency to slow water and air movement. Such a soil is highly plastic, but becomes sticky when too wet, and hard and cloddy when too dry. The expansion and the contraction on wetting and drying are very great. The water-holding capacity of a clayey or silty soil is high. Such soils are spoken of as heavy because of their working qualities in the field in contrast to the easily tilled sandy soils.

42. The mineralogical and chemical characteristics of soil separates.—From the mineralogical standpoint there are often considerable differences between the soil separates, especially when the sands and clays are compared. Quartz would naturally be expected to persist and because of its low solubility would very soon be dominant not only in the coarser separates but in the silt and clay as well. Other minerals, such as the feldspars, hornblende, mica, and augite being less resistant would concentrate in the finer separates. This tend-

[1] The colloidal state—when material is in a very fine state of division, approaching but not attaining a molecular condition (true solution), it assumes certain characteristic properties, such as high absorption for water, gases, and salts in solution. It may also, under certain conditions, cause a marked increase in plasticity and cohesion. The colloidal condition is purely physical and depends on fineness of division, the particles being molecular complexes. Material in a colloid state is heterogeneous and is dispersed through a second material called the dispersive medium.

ency together with the formation, as weathering proceeds, of the fine coloidal-like epidote, chlorite and similar groups, should in general keep the percentage of minerals other than quartz higher in the finer portions of a soil.[1] The following data sustain this assumption:

TABLE XII

MINERALS OTHER THAN QUARTZ IN THE SANDS AND SILTS OF VARIOUS SOILS [2]

Soils	Minerals Other Than Quartz in	
	Sands	Silts
12 Residual	15%	21%
6 Glacial and Loessial	12	15
4 Marine	5	18
3 Arid	37	42

It is to be seen immediately that in every case the silt carries a large quantity of the important soil-forming minerals and a smaller amount of quartz than does the sand. This reveals at least one of the reasons for the greater fertility and lasting qualities of fine-textured soils as far as agricultural operations are concerned. It is important to note, however,

[1] A petrographic analysis as now developed is very unsatisfactory as it throws practically no light on the character of the clay group because of the extreme fineness of this material. Even for silt the results are unsatisfactory and difficult to express quantitatively. The correlation of a petrographic analysis and productivity is vague.

[2] McCaughey, W. G., and Fry, W. H., *The Microscopic Determination of Soil-forming Minerals;* U. S. Dept. Agr., Bur. of Soils, Bul. 91, 1913. See also, Plummer, J. K., *Relation of the Mineralogical and Chemical Composition to the Fertility Requirements of North Carolina Soils;* N. C. Agr. Exp. Sta., Tech. Bul. 9, 1914. Plummer, J. K., *Petrography of Some North Carolina Soils and its Relationship to their Fertilizer Requirements;* Jour. Agr. Res., Vol. V, No. 13, pp. 569-581, 1915. Robinson, W. O., *The Inorganic Composition of Some Important American Soils;* U. S. Dept. Agr., Bul. 122, Aug., 1914. Shorey, F. C., *et al., Calcium Compounds in Soils;* Jour. Agr. Res., Vol. VII, No. 3, pp. 57-77. Jan., 1917.

that, although quartz is the predominating mineral in sands, all the common soil-forming minerals are usually accessory.[1]

It is interesting in passing to observe the differences exhibited by the various soil provinces although the number of samples shown by Table XII are far too small for definite conclusions. The marine soils are particularly low compared with the residual and glacial, due to the hard usage which the soil material of the former has received. No significant differences exist between the glacial and residual soils. The arid soils, however, are markedly higher in the important minerals due to the suppression of chemical weathering and the activity of the physical agents. The silica in such soils is held as complex silicates, which carry the elements that are so important in plant development. Although these data are based on but a few samples, they are so concordant with what would naturally be expected that these general conclusions cannot be avoided.

The mineralogical examination has revealed a larger percentage of such minerals as feldspars, mica, hornblende, and the like, in the finer separates. A larger percentage of the important nutrient elements would, therefore, be expected in those groups. The following data,[2] compiled from work performed by the United States Bureau of Soils, substantiate this assumption. (See Table XIII, page 78.)

It is evident that the finer portions of soil are in general

[1] Below is given the mineralogical description of a loessial silt loam of the Marshall Series from Missouri: Robinson, W. O., *The Inorganic Composition of Some Important American Soils;* U. S. Dept. Agr., Bul. 122, Aug., 1914.

Very fine sand—minerals other than quartz, 20 per cent. Orthoclase, 10 per cent. Muscovite, 2 per cent. Biotite, magnetite, epidote, albite, labradorite, oligoclase, tourmaline, zircon, garnet, and augite are also present.

Silt—Minerals other than quartz, 34 per cent. Orthoclase, 4 per cent. Muscovite, 4 per cent. Biotite, magnetite, epidote, albite, labradorite, oligoclase, tourmaline, rutile, glaucophane, hornblende, and augite are also present.

[2] Failyer, G. H., and Others, *The Mineral Composition of Soil Particles;* U. S. Dept. Agr., Bur. Soils, Bul. 54, 1908.

TABLE XIII

CHEMICAL COMPOSITION OF VARIOUS SOIL SEPARATES

SOILS	NUMBER OF SAMPLES.	PERCENTAGE OF P_2O_5 IN			PERCENTAGE OF K_2O IN			PERCENTAGE OF CaO IN		
		SAND	SILT	CLAY	SAND	SILT	CLAY	SAND	SILT	CLAY
Crystalline Residual ...	3	.07	.22	.70	1.60	2.37	2.86	.50	.82	.94
Limestone Residual ...	3	.28	.23	.37	1.46	1.83	2.62	12.26	10.96	9.92
Coastal Plain.	7	.03	.10	.34	.37	1.33	1.62	.07	.19	.55
Glacial and Loessial ...	10	.15	.23	.86	1.72	2.30	3.07	1.28	1.30	2.69
Arid	2	.19	.24	.45	3.05	4.15	5.06	4.09	9.22	8.03

richer in phosphoric acid, potash and lime than the coarser. As would be expected the sands, silts, and clays of arid soils show less difference than those of the other provinces. Under arid conditions the sands have not as yet become depleted of their store of essential elements. Average figures compiled from Hall's analyses [1] of soils from southeastern England corroborate the data already noted. In addition, Hall shows that the magnesia, iron, and alumina are higher in the finer separates while there is considerably more silica in the sand groups.[2]

[1] Hall, A. D., and Russell, E. J., *Soil Surveys and Soil Analyses;* Jour. Agr. Sci., Vol. IV, Part 2, p. 199, 1911. Also *A Report of the Agriculture and Soils of Kent, Surrey, and Sussex;* Board of Agriculture and Fisheries, 1911. See also: Loughridge, R. H., *On the Distribution of Soil Ingredients among Sediments Obtained in Silt Analyses;* Amer. Jour. Sci., Vol. VII, p. 17, 1874. Puchner, H., *Über die Vertielung von Nährstoffen in den Verschieden Feinen Bestandteilen des Boden;* Landw. Ver. Stat., Band 66, Seite 463-470, 1907. Hendrick, J., and Ogg, W. J., *Studies of Scottish Drift Soil, Part I. The Composition of the Soil and of the Mineral Particles Which Compose It;* Jour. Agr. Sci., Vol. VII, Part 4, pp. 458-469, Apr. 1916. McGeorge, W. T., *Composition of Hawaiian Soil Particles;* Haw. Agr. Exp. Sta., U. S. Dept. Agr., Bul. 42, Jan., 1917. Robinson, G. W., *Studies of the Palæzoic Soils of North Wales;* Jour. Agr. Res., Vol. VIII, Part 3, pp. 380-381, June, 1917.

[2] McGeorge's investigation of the residual volcanic soils of Hawaii shows some noteworthy exceptions to the work of Failyer and Hall in

TABLE XIV

COMPOSITION OF SOIL SEPARATES (HALL)

SEPARATE	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	P_2O_5
Coarse Sand (1—.2 mm.)	93.9	1.6	1.2	.4	.5	.8	.05
Fine Sand (.2—.04 mm.)	94.0	2.0	1.2	.5	.1	1.5	.1
Silt (.04—.01 mm.)	89.4	5.1	1.5	.8	.3	2.3	.1
Fine Silt (.01—.002 mm.)	74.2	13.2	5.1	1.6	.3	4.2	.2
Clay (Below .002 mm.)	53.2	21.5	13.2	1.6	1.0	4.9	.4

43. Value of a mechanical analysis.—It is evident that a proper interpretation of a mechanical analysis will throw considerable light on the probable condition of a soil, especially physically. To the trained observer the preponderance of sand, clay, or silt signifies the probable presence of certain physical properties, which may affect the plant not only mechanically but physiologically as well, through air, water, and nutrient movement.

The chemical and mineralogical phases of such interpretation are also worthy of consideration, as the proportion of the various separates determines whether the essential nutrient will be present in sufficient quantities to permit normal crop growth. Thus a mechanical analysis not only enlightens as to the general properties of a given soil, but when correlated with other factors is to some extent a criterion of agricultural value and crop adaptation. Some authors maintain that in the investigation of any soil a mechanical analysis should first be made, as it throws much light on many properties of a soil.

44. Soil class—how soils are named.—As a soil is not composed of particles of uniform size and shape, a blanket term is needed, which will not only give some idea of the textural character of the mixture, for every soil is a mixture,

that he found the lime and magnesia higher in the coarser particles and the silica higher in the finer separates. McGeorge, W. T., *Composition of Hawaiian Soil Particles;* Haw. Agr. Exp. Sta., Bul. 42, Jan. 1917.

but at the same time will name it in such a manner as to reveal its general physical peculiarities and proportions. For this *class* names, such as sandy loam, loam, silt loam, and the like, are used. Class differs from texture, however, in that it has reference to the properties exhibited by a soil rather than

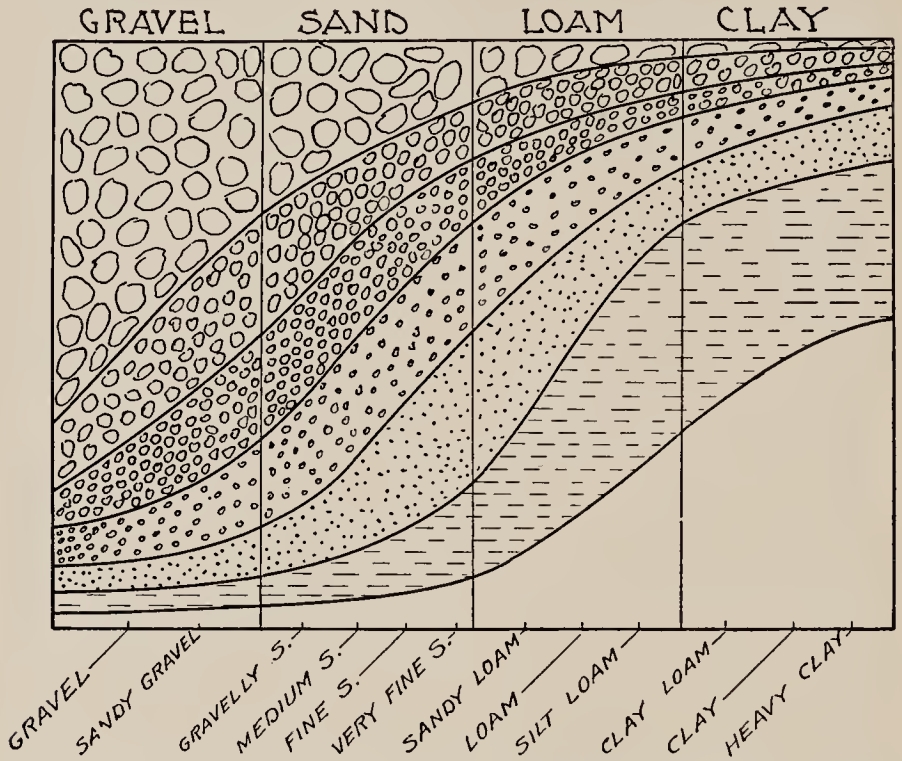


FIG. 16.—Diagram showing in a general way the mechanical composition of gravel, sand, loam and clay soils and indicating in addition how some of the more common field names arise.

to any absolute grain size. Consequently, there may be a number of class names depending on the proportionate mixtures of different sized particles that occur in the field.

Class names have originated through long centuries of agricultural observations, but of late they have been more or less standardized because of the necessity of a definite nomenclature. In general, the names used for the soil classes are the

same as those employed in mechanical analyses to designate the soil separates. This is rather unfortunate, but it obviates the increase of technical terms and a little care will prevent confusion in this regard. Four fundamental groups of soil are recognized: gravel, sand, loam, and clay (See Fig. 16). Gravel is a soil constituent that does not often occur alone and is not of great importance agriculturally because of its low fertility. The other three, however, either alone or in combination make up most of the arable soil. Their average mechanical analyses are set forth in Table XV.

TABLE XV

MECHANICAL ANALYSES OF SANDY, LOAMY AND CLAYEY SOILS[1]

SEPARATES	SANDY SOIL	LOAMY SOIL	CLAYEY SOIL
	%	%	%
1. Fine Gravel	2	2	1
2. Coarse Sand	15	5	3
3. Medium Sand	23	5	2
4. Fine Sand	37	15	8
5. Very Fine Sand	11	17	8
6. Silt	7	40	36
7. Clay	5	16	42

The sand group includes all soils of which the silt and clay separates make up less than 20 per cent of the material by weight. Its properties are, therefore, characteristically sandy in contrast to the more open character of gravel and the stickier and more clayey nature of the heavier groups of soil. A soil to be clay must carry at least 30 per cent. of the clay separate. It may even have more silt than clay but, since the silt particles impart clayey characters, as long as the percentage of clay is 30 or above, the class name must remain clay.

[1] Whitney, M., *The Use of Soils East of the Great Plains Region;* U. S. Dept. Agr., Bur. Soils, Bul. 78, p. 12, 1911.

The loam class is rather difficult to explain. In mechanical composition it is more or less midway between sand and clay. A loam may be defined as such a mixture of sand, silt, and clay particles as to exhibit sandy and clayey properties in about equal proportions. It is a half and half mixture on the basis of properties, although the sum of the sands and the sum of the silt and clay are generally near 50 per cent., respectively. (See Fig. 16.) Because of the marked intermixture of coarse, medium, and fine particles, loams are usually soils of good physical character. They generally possess the desirable qualities both of sand and clay without exhibiting those undesirable properties, such as extreme looseness and low water capacity on the one hand and stickiness, compactness, and slow air and water drainage on the other. Most of the better soils are some type of loam.

It is obvious that in the field not only various kinds of gravelly, sandy, loamy, and clayey soils must occur, but the groups must grade into each other, thus giving rise to a considerable number of field names. (See Fig. 16.) These field names are listed below:

Common Class Names

1. Gravel
2. Coarse sand
3. Medium sand.
4. Fine sand
5. Very fine sand
6. Coarse sandy loam
7. Sandy loam
8. Fine sandy loam
9. Very fine sandy loam
10. Loam
11. Silt loam
12. Silty clay loam
13. Clay loam
14. Clay
15. Heavy clay
16. Sandy clay

The meaning of these names should be clear except possibly those into which the loam group is divided. Loam, as already explained, refers to a soil possessing in about equal amounts the properties imparted by the various separates. If, however, we have practically the same condition but with one

size of particle predominating, the name of that particular separate is prefixed, giving still more data regarding the soil in question. Thus, a loam in which clay is dominant will be classified as a clay loam. In the same way, we may have a sandy loam, silt loam, and so on. It is to be noted that the loams make up half of the class names. In fact, the greater proportion of the soils so far classified in the United States are loams, which is fortunate as the loams in general are more favorable for crop production than any of the other class groups.

The mechanical analyses of some of the more common classes[1] are listed in Table XVI:

TABLE XVI

	Fine Gravel	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay
Coarse Sands....	12	31	19	20	6	7	5
Sands	2	15	23	37	11	7	5
Fine Sands.....	1	4	10	57	17	7	4
Sandy Loams....	4	13	12	25	13	21	12
Fine Sandy Loams	1	3	4	32	24	24	12
Loams	2	5	5	15	17	40	16
Silt Loams.....	1	2	1	5	11	65	15
Sandy Clays.....	2	8	8	30	12	13	27
Clay Loams.....	1	4	4	14	13	38	26
Silty Clay Loams	0	2	1	4	7	61	25
Clays	1	3	2	8	8	36	42

It is evident that a mechanical analysis of a soil is nothing more or less than an expression of class, and the inferences that may be derived from either are in general the same. This leads to a consideration of class determination.

45. Determination of soil classes.—The common method of class determination is that employed in the field. It con-

[1] Whitney, M., *The Use of Soils East of the Great Plains Region;* U. S. Dept. Agr., Bur. Soils, Bul. 78, p. 12, 1911.

sists in an examination of the soil as to color, an estimation of its organic content, and, especially, a testing of the "feel" of the soil in order to decide as to the class name. Probably as much can be judged as to the texture and class of a soil merely by rubbing it between the thumb and the fingers or in the palm of the hand as by any other superficial means. This method is used in all field operations, especially in soil survey work. It really consists in sufficiently recognizing the textural composition of a soil that the class name may be determined.[1]

The accuracy of such a determination depends largely on experience. Inaccuracies are likely to occur in distinguishing between the various finer grades of soil; for this reason, more nearly exact methods are necessary at times, especially in checking soil survey work or in carrying out investigations in which absolute accuracy is required.

As a mechanical analysis of a soil is really a percentage expression of texture, it presents an exact method for class determination. For detailed work, somewhat complicated tables[2] have been arranged; but the following diagram

[1] Key for the practical classification of mineral soils:

I. Soils possessing the properties of one size of particle largely.
   1. Particles very large ..... *Gravel*
   2. Particles apparent to eye; feel gritty and non-plastic ..... *Sands*
   3. Particles very small; soil very plastic when wet, hard when dry ..... *Clay or Sandy Clay*

II. Soils possessing the properties of a number of sizes of particles—a mixture.
   1. A fairly equal exhibit of sandy and clayey properties ..... *Loam*
   2. A mixture but with sand predominating... *Sandy Loam*
   3. A mixture but with silty character dominant. The soil has a floury or talc feel and is quite plastic when wet ..... *Silt Loam*
   4. A mixture but with clayey characters very apparent. Soil is very plastic and approaches a clay in character ..... *Clay Loam*

[2] Bur. of Soils, *Soils Survey Field Book*, p. 17; U. S. Dept. Agr., Bur. Soils, 1906. Also, Bur. Soils, Bul. 78, p. 12, 1911.

(Fig. 17), devised by Whitney,[1] presents a simple method for the identification of a soil from a mechanical analysis. The convenience of such a triangular representation is obvious.

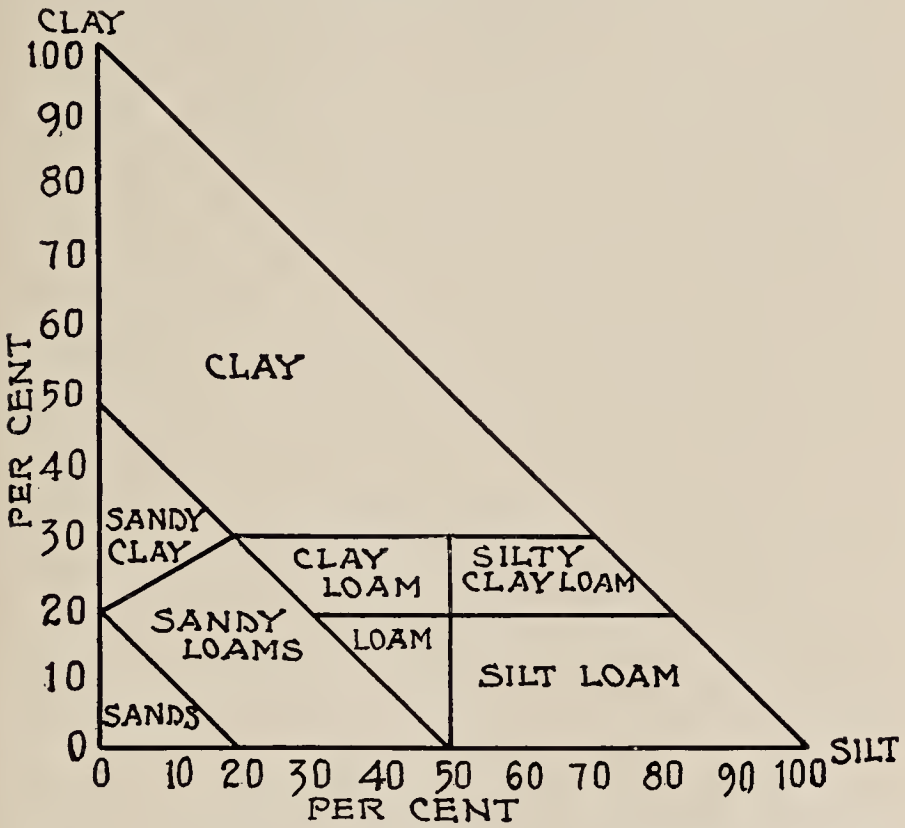


FIG. 17.—Diagram for the determination of class from a mechanical analysis. In using the diagram the points corresponding to the percentages of silt and clay are located on the silt line (abscissa) and clay line (ordinate) respectively. Perpendiculars at these points are then projected inward until they intersect. The name of the compartment in which the intersection occurs gives the class name of the soil in question.

46. Soil survey classification—soil type.—The function of the soil survey is to investigate the nature and occurrence

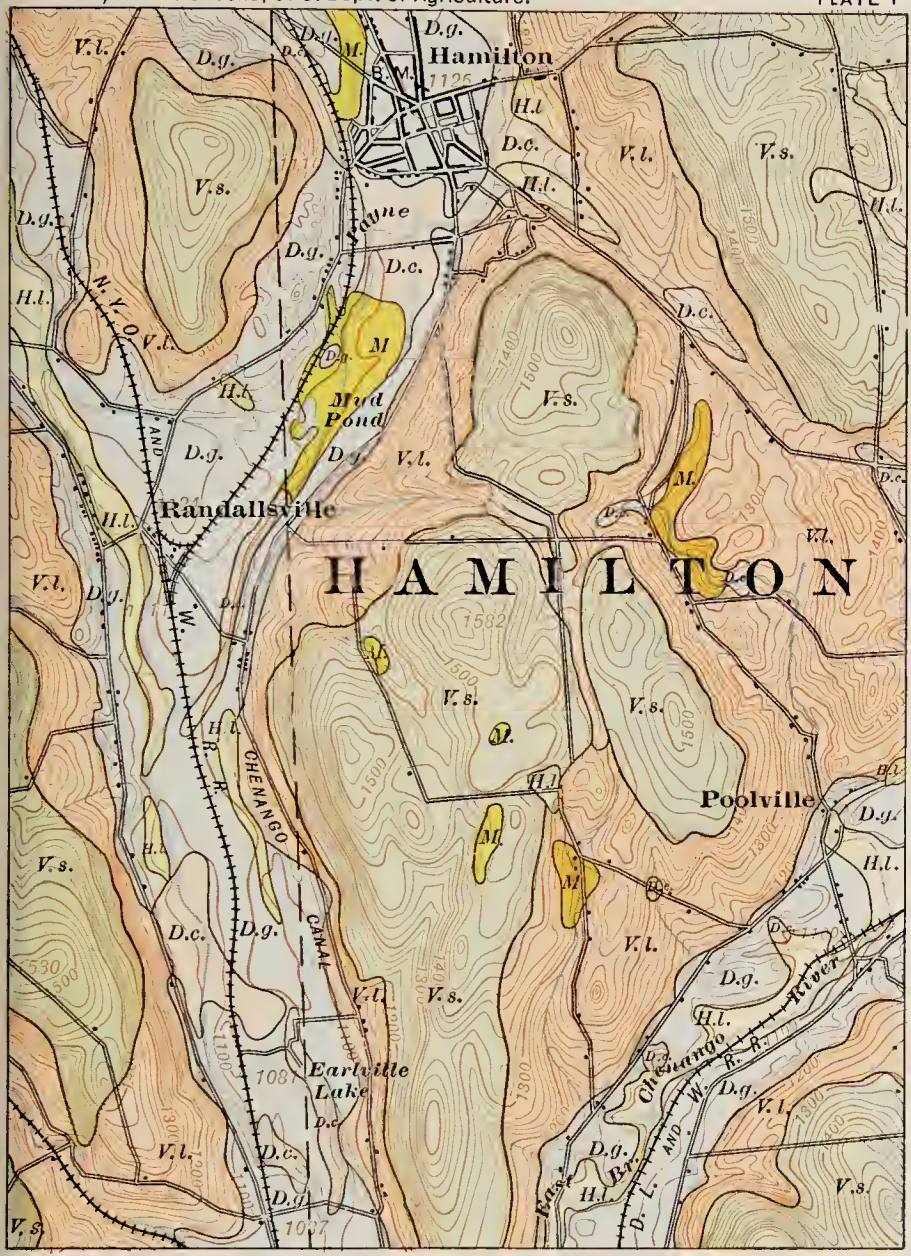
[1] Whitney, M., *The Use of Soils East of the Great Plains Region;* U. S. Dept. Agr., Bur. Soils, Bul. 78, p. 13, 1911.

of soils in the field. The soils thus studied are classified into areas having approximately the same crop relations and tillage properties. The location of the areas of each kind of soil is represented on an adequate base map, and their character and chief economic and agricultural relations are described in a printed report accompanying the soil map.[1] (See Fig. 18).

In classifying soils six primary factors are considered. These, beginning with the broadest, are as follows: (1) temperature, (2) precipitation, (3) agency of formation, (4) kind of material, (5) special properties other than texture, and (6) texture. It is obvious that certain soils may be of different texture but alike in all other ways. Their climatic environments, mode of formation, rock materials, and specific properties, such as color, drainage, organic condition, and lime content may be approximately the same. Such soils are grouped together as *series* and the series are named, generally from some town, county, or river of the near vicinity. Thus we have the Norfolk series of the Atlantic coastal plain; the Cecil soils of the Piedmont Plateau; the Ontario series arising from the calcareous till of central New York state and the Marshall soils of the loessial region of the Middle West. The soils within each series are approximately the same except for class distinction.

The soil *type* is the unit of classification and may be defined as an area of soil alike in all characteristics, including crop productiveness. Obviously any soil class of any particular series would be a soil type. Norfolk sandy loam, Ontario loam, and Cecil clay are examples of how soil types are designated. The type designation is especially valuable in soil description since the series name expresses in one word a great number of conditions, which otherwise would require detailed explanation. The class name establishes in addition the textural condition.

[1] For further information consult one of the numerous soil survey reports as published by the U. S. Dept. Agr., Bur. of Soils.



Volusia silt loam | Volusia loam | Dunkirk gravelly loam | Huntington loam | Dunkirk clay | Muck

FIG. 18.—Part of the Madison County, New York, soil map showing the topography and drainage and the relation of the various soil types to one another. The Volusia series arises from the ground moraine, the Dunkirk from glacial lake sediments while the Huntington is alluvial. Note the varying elevation of the muck.

While the principles of series identification are too complicated to be expanded farther at this time, enough has been said to establish the importance of accurate soil classification. Unless soils are accurately named in soil survey work, the map and its accompanying report are useless.

Soil texture and class are thus the basis for practical soil study, whether regarding some particular property or a general condition, such as crop adaptation. No matter what the phase of soil study may be, texture and class are sure to have some important influence and must be considered in the investigation.

47. Soil structure.—While texture is of great importance in determining the general characteristics of a soil, it is evident that the arrangement as well as the size of the particles must exert some influence. The term *structure* is used to refer to this arrangement or grouping. It is at once apparent that soil conditions—such, for example, as air and water movement, heat transference, and the like—will be as much affected by structure as by texture. As a matter of fact, the great changes wrought by the farmer in making his soil better suited as a foothold for plants are structural rather than changes in texture. The compacting of a light soil or the loosening of a heavy one is merely a change in the arrangement of the soil grains and in the condition and nature of the colloidal complexes[1] thereof.

From the standpoint of size and arrangement of particles there are really two classes of soils, those of single grain structure and those which are complex, the particles both large and small being bound together by indefinite colloidal complexes. The former condition is of course best exemplified by a sand. Such a soil is loose and open with large individual pore spaces and ready circulation of air and water. The com-

[1] Material in a colloidal state has a great deal to do with all soil phenomena. Its characteristics and influence must be kept constantly in mind in soil study.

plex structure is best developed in clay. Here the soil granules are made up of many particles, the colloidal material acting as a binding agent. Such a soil may be loose, open and friable, if granules of the proper size and nature are developed. On the other hand, improper handling may run the complexes together and an impervious and puddled condition may result. The sand will obviously permit of no very great structural change, while the clay can be modified very materially by certain field manipulations.

The ideal structural condition is most likely to occur in a loam soil. In such a soil some of the particles are large and function separately; others are medium in size and tend to form the nuclei around which smaller particles, both colloidal and non-colloidal, may cluster to form granules, or aggregates. There are thus a few large pore spaces which facilitate drainage, and numberless small openings in which water is retained. Air, therefore, finds easy movement and sanitation is promoted. In promoting such a condition the organic matter plays an important part. It usually exists as a dark, partially decayed material, often colloidal in nature. It pushes apart the grains and lightens the soil, and contributes much in bringing about the loamy condition so favorable to plant development. It is a valuable addition also on account of its water-holding capacity and its nitrogen content.

48. Specific gravity of soils.—The texture, as well as the structure of a soil, has considerable influence on certain physical conditions other than those already mentioned. One of these is weight. The weight of a soil is determined by two factors: the weight of the individual particles and the amount of the space occupied by the soil material. The former is determined by the chemical and mineralogical character of the particles, the latter by their structural arrangement. Thus, if the soil particles are heavy and the soil is compact, the weight of any given volume, a cubic foot for example, will be high.

The specific gravity[1] of a soil is obviously the average specific gravity of the particles. It is unaffected by the structure, remaining the same whether the soil is loose and open or compact and unaërated. Although a great range is observed in the specific gravities of the common soil minerals[2], the specific gravity of a purely mineral soil varies between the narrow limits of 2.6 and 2.7. This occurs because quartz and feldspar, whose specific gravities are about 2.65 and 2.57, respectively, usually make up the bulk of the mineral portion of most soils. The fineness of the particles seems to have no appreciable effect on specific gravity as shown by the following data from Whitney and Smith[3]:

TABLE XVII

SPECIFIC GRAVITY OF SOIL SEPARATES

SEPARATES	WHITNEY	SMITH
Fine gravel	2.64	2.67
Coarse sand	2.65	2.64
Medium sand	2.64	2.64
Fine sand	2.65	2.69
Very fine sand	2.68	2.66
Silt	2.69	2.65
Clay	2.83	2.66

[1] Specific gravity is expressed as a ratio of the weight of any volume of a substance to the weight of an equal volume of some other substance taken as a standard unit. Liquids and solids are usually compared with water at its maximum density (4° C.).

[2] The specific gravities of some of the common soil minerals are as follows:

Quartz	2.60-2.70	Apatite	3.20
Orthoclase	2.57	Kaolinite	2.60-2.63
Plogioclase	2.62-2.76	Serpentine	2.50-2.65
Muscovite	2.76-3.00	Chlorite	2.65-2.92
Biotite	2.70-3.10	Epidote	3.25-3.50
Hornblende	3.05-3.47	Hematite	4.90-5.30
Augite	3.20-3.60	Limonite	3.60-4.00

[3] Whitney, M., *Some Physical Properties of Soils;* U. S. Dept. Agr., Weather Bur., Bul. 4, 1892. Smith, Alfred, *Relation of the Mechanical Analysis to the Moisture Equivalent of Soils;* Soil Sci., Vol. IV, No. 6, p. 472, Dec., 1917.

The only marked variation here observed is in the clay separates of the first column. This may be due to the concentration of the iron-bearing silicates in this grade and would thus be an apparent rather than a real variation.

Only one condition may vary the specific gravity of any soil. This is the quantity of organic matter present. As the specific gravity of organic matter usually ranges from 1.2 to 1.7, the more that is present the lower will be the figure for any given soil. A purely organic soil, such as muck, presents a variable specific gravity ranging from 1.5 to 2.0, according to the amount of inorganic wash it has received from external sources. Some highly organic mineral soils may drop as low as 2.3. Nevertheless, for general calculations, the average arable soil may be considered to have a specific gravity of about 2.65.

FIG. 19.—Drawing showing the type of picnometer generally used in determining the specific gravity of soil. The ground-glass stopper is perforated.

The specific gravity of a soil is generally determined by means of a picnometer, a bottle fitted with a perforated ground-glass stopper and accurately calibrated (Fig. 19). By comparing the weight of the total water held by the bottle, usually 50 cubic centimeters, with the weight of the water when any given amount of dry soil, say 5 grams, is present in the bottle, the weight of the water displaced by the soil can be determined and the specific gravity calculated therefrom.[1]

[1] Below will be found a sample calculation:

Weight of picnometer	23.257 grs.
Volume of picnometer	50 cc.
Wt. of picnometer + 5 grs. soil + X grs. water	76.347 grs.
Wt. of picnometer + 5 grs. soil	28.257 grs.
Wt. of X grs. water	48.090 grs.
Water displaced (50 — 48.09)	1.910 grs.

$$\text{Specific gravity} = \frac{5.00}{1.91} = 2.61 +$$

49. Volume weight of soils.—The actual weight of dry soil in any given volume is generally expressed by volume weight, a figure indicating the number of times heavier the dry soil is than the water that will occupy the same soil volume. Thus, if the dry soil in a cubic foot of space weighs 99.8 pounds, the volume weight would be $99.8 \div 62.42$ or 1.6. The volume weight differs from specific gravity in that it compares the weight of the dry soil to the weight of water that will occupy the total soil volume—that is, the space usually filled by soil particles, soil air, and soil water. Specific gravity, however, compares the weight of the dry soil to that of water that will occupy only the volume of the particles alone, taking no consideration of the normal pore space. It is consequently always the higher figure.[1]

This volume weight figure depends on the texture of the soil, the structure and the amount and condition of the organic matter. The particles of sandy soils always tend to lie in close contact, thus increasing the weight of soil to a given volume. The particles of the finer soils, such as silt loams, clay loams, and clays, on the other hand, being smaller and lighter, do not lie so closely together. A greater total pore space is, therefore, usually present in the finer soils and the volume weight is correspondingly lowered. Mineral soils may range in volume weight from 1.10 to 1.35 for clay to 1.55 to 1.70 for sand.[2] The influence of texture on the volume weight is thus evident.

The structural and organic condition of soils often produces wide variation in volume weight. When a soil is loos-

[1] As a soil is compacted, its volume weight increases due to the increase volume occupied by the soil particles and the corresponding decrease in pore space. If it were possible to compact a soil to a completely solid condition, its volume weight would approach its specific gravity as a limit. Specific gravity represents, therefore, 100 per cent. soil particles. Volume weight in comparison indicates the proportion of space occupied by the soil particles.

[2] Sandy soils are commonly spoken of as light soils, while clays are called heavy. Such usage refers to working properties and has no reference to actual weights.

ened through tillage, it becomes lighter for any given volume. The addition of organic matter has the same effect, since the particles are spread wider apart and the air and water spaces increased. The specific gravity figure of a sandy loam of 1.55 may readily be lowered to 1.45 by an increase of organic material. Some loams high in organic matter may drop as low as 1.1 in specific gravity while muck often reaches the low figure of .40.

In the field the volume weight of a soil may be estimated by driving a cylinder of known volume into the ground and obtaining thereby a core of natural soil. By weighing the soil and then determining the amount of water that it holds, the amount of absolutely dry soil may be ascertained. Dividing this by the weight of an equal volume of water gives the figure for volume weight.[1]

A laboratory determination may be made by putting the soil into a receptacle of known volume and weighing it. From the weight of the absolutely dry soil and the weight of an

[1] The rubber tube method has proven very convenient for the field determination of volume weight. A hole is bored in the soil to the required depth by a specially constructed auger, the soil being carefully removed and later oven dried. A very thin-walled tubular rubber bag of the size of the auger hole is carefully inserted in the hole previously bored. The tubular bag is then filled with water flush with the surface of the soil. The water is measured and the volume of the soil removed is thus determined. Knowing the weight of dry soil and its original volume, the volume weight may be calculated. The experimental error of the method is rather low.

Israelsen, O. W., *A New Method of Determining Volume Weight;* Jour. Agr. Res., Vol. XIII, No. 1, pp. 28-35, April, 1918.

The paraffin-immersion is valuable with heavy soils. Small pieces of soil are dried, weighed and then coated very thinly with paraffin, just sufficiently to prevent the entrance of water, yet not enough to introduce serious experimental error. The weight of the water displaced by a number of such pieces may be determined easily by the use of a graduated cylinder.

Shaw, C. F., *A Method for Determining the Volume Weight of Soil in Field Condition;* Jour. Amer. Soc. Agron., Vol. IX, No. 1, pp. 38-42, 1917. See also, Trnka, R., *Eine Studie über einige physikalishchen Eigenschaften des Bodens;* Internat. Mitt. of Bodenkunde, Bd. IV, Heft 4-5, S. 363-380, 1914.

equal volume of water, the volume weight may be calculated. This method will give only approximate results, however, as the structural relationships are more or less artificial.[1]

50. Actual weight of soil.—When the volume weight of a soil is known, its weight in pounds to the cubic foot may be found by multiplying by 62.42. Soils may vary in weight from 68 to 80 pounds for clays and silts to 100 to 110 pounds for sands. The greater the organic content, the less is this weight to the cubic foot. A muck soil often weighs as little as 25 or 30 pounds. This weight, of course, is for absolutely dry soil and does not include the water present, which may be much or little, according to circumstances.

The actual weight of soil may also be expressed in acre-feet. An acre-foot of soil refers to a volume of soil one acre in extent and one foot deep. In the same way we may have an acre-eight-inches or an acre-six-inches. The weight of an acre-foot of soil usually varies from 3,500,000 to 4,000,000 pounds. The standard usually adopted is 2,000,000 pounds, being the weight of average soil to a depth of $6^2/_3$ inches. The value of knowing the actual weight of a soil lies in the possibility of calculating thereby the amount of water, the amount of organic matter, or the actual number of pounds of the mineral constituents present in the soil. Such information affords another means of comparing two soils.

51. Pore space of soil.—The pore space of soil is occupied by air and water in constantly varying proportions. The amount of this pore space is determined by the texture and the structure of the soil. As already emphasized, the coarser

[1] A comparison of the four methods is given by Israelsen, O. W., *A New Method for Determining Volume Weight;* Jour. Agr. Res., Vol. XIII, No. 1, p. 32, 1918.

Average Volume Weight of Tehama Clay to a Depth of 60 Inches.

Laboratory method on disturbed soil	$1.35 \pm .008$
Rubber tube method	$1.74 \pm .010$
Iron cylinder method	1.73
Paraffin-immersion method	$1.73 \pm .035$

soils are heavy due to the close contact of the particles, while the finer soils are much lighter due to the tendency of the small particles to resist compaction.[1] This means that soils such as sands and sandy loams contain less pore space than silt loams, clay loams, and clays. While the heavier soils have more combined air and water space, the individual spaces are much smaller than in the sands, which accounts for the slow air and water drainage in the former and the ease with which such phenomena take place in the lighter soils.

A very simple formula may be used to calculate pore space, providing the specific gravity and volume weight are known. It is subject to considerable inaccuracy, however, because of the presence of colloidal matter, the exact influence of which cannot be determined.

$$\% \text{ Pore Space} = 100 - \left(\frac{\text{vol. wt.}}{\text{sp. gr.}} \times \frac{100}{1}\right)^{[2]}$$

A soil having a volume weight of 1.6 and a specific gravity of 2.6 has, according to this formula, 38.5 per cent. of pore space. A soil in which the above figures are 1.1 and 2.5, respectively, possesses 56 per cent. of air and water space.

The following figures taken from King [3] illustrate the relation that texture and, to a certain extent, structure also occupies in relation to soil pore space:

[1] Sandy soils are generally spoken of as loose, while clays are called compact. The term compact is thus used in the sense of hard, unyielding, stiff, or impenetrable, and does not indicate that the pore space of clay is less than that of a sandy soil.

[2] It has already been explained in a previous footnote (see under volume weight) that the specific gravity of a soil represents 100 per cent. soil material or the weight of absolutely solid soil. Volume weight indicates in comparison thereto, the soil material actually present. The ration of the specific gravity to the volume weight when multiplied by 100 becomes the percentage of the soil volume occupied by the soil particles.

[3] King, F. H., *Physics of Agriculture;* published by the author, Madison, Wisconsin, 1910.

TABLE XVIII

PERCENTAGE PORE SPACE IN SOILS OF DIFFERENT TEXTURE

Sandy soil	32.5
Loam	34.5
Heavy loam	44.1
Loamy clay	45.3
Clayey loam	47.1
Clay	48.0
Heavy clay	52.9

The pore space in a normal soil is occupied by water and air. If the water content is low, the air space is large, and *vice versa.* Thus the relationships of the total pore space and the size of the individual spaces to the amount of air and water contained, to their movement through the soil, to soil sanitation, to root extension, to bacterial action, and to cropping conditions in general, become apparent. It is the regulation of this pore space that is really important in any structural consideration. The effect on plant growth of a change of pore space is the only test of its advisability.

52. Soil particles—their number and surface exposed. —Since soil particles run to extremely small diameters, the number in any given volume is very large, especially when fine-textured soils are considered. However, any calculation of the number of particles present in a soil is open to great inaccuracy; first, because it is impossible to get a correct figure for the average diameter of the particles of any soil or of the various groups of separates that go to make it up; and, secondly, because it must be assumed in the calculation that the particles are spherical. The presence of colloidal matter, especially in the heavier soil types, introduces an error the magnitude of which must be very great. Nevertheless, such a calculation, even if very inaccurate, gives some idea as to the immense number of grains that are present even in the

coarser soils. A few figures are given in Table XIX for some of the average soil classes [1] established by the Bureau of Soils:

TABLE XIX

APPROXIMATE NUMBER OF PARTICLES TO A GRAM OF VARIOUS SOIL CLASSES [2]

Soil Class	Number of Particles to the Gram
Sands	2,287,000,000
Sandy loams	5,483,000,000
Loams	7,332,000,000
Clay loams	11,877,000,000
Clays	19,177,000,000

An important property of the surface of the grains is the tendency toward the retention of soluble material in a partially or wholly available condition for plant use. This power, designated as absorption, is exhibited to a high degree by fine soils, in which the individual pore spaces are small and the amount of surface exposed is large, due to the presence of considerable colloidal matter. This capacity is an especially important factor in the economical use of fertilizer salts. Absorption may also, by bringing materials into closer contact, hasten or retard certain chemical actions. Changes may thus

[1] The mechanical analyses of these particular classes are given on page 83.

[2] The number of particles in any soil sample may be arrived at from a mechanical analysis and the diameters that limit each group. Using the average diameter of each group together with the percentage of the groups in a given sample, the number of particles may be calculated by the following formula:

$$\text{Number of particles in a sample of soil} = \frac{\text{Weight of sample in grams}}{1/6\,\pi\,D^3 \times 2.65}$$

The formula $1/6\,\pi\,D^3$ is that used for determining the volume of a sphere, the diameter in this case being expressed in centimeters. When multiplied by the average specific gravity of soil particles the weight of an average particle is obtained in grams. In the above calculations, 2.7 was used instead of 2.65.

be expected to go on in the soil that would not take place in the laboratory beaker. The relation of this absorption to bacterial activity also cannot be overlooked.

The minerals of the soil are all very resistant to solution; if they were not, they would long ago have been leached away. Such materials, while almost insoluble under ordinary circumstances, allow appreciable amounts of nutrients to appear in the soil solution, because of the immense amount of surface exposed, although the specific solubility remains the same.

In order to present some idea of the internal surface of ordinary soils, a few figures are given on the same soil classes for which the number of particles have already been calculated:

TABLE XX

APPROXIMATE INTERNAL AREA OF SEVERAL AVERAGE SOIL CLASSES [1]

Soil Class	Square Inches per Gram	Square Feet per Pound	Acres per Acre-Foot of 3,500,000 lbs.
Sands	89	280	22,549
Sandy loams	213	671	53,965
Loams	294	926	74,410
Clays loams	430	1354	108,830
Clays	653	2057	165,270

While these figures are as grossly inaccurate as those regarding the number of particles, they tend to emphasize the tremendous internal surface possessed by even the coarser soils. The data presented for an acre-foot of soil, while almost too large for adequate comprehension, are probably much too low. It is not to be wondered at that the slowly soluble minerals are able to supply sufficient nutrients to the

[1] When the approximate number of particles and their sizes in any given weight of soil are known, the internal surface may be calculated by the following formula:

$$\text{Surface} = \pi D^2 \times \text{number of particles.}$$

crop growing on the soil, when such a large amount of surface is continually available for chemical action.

53. Resume.—The discussion of the soil particle as to its size, its classification, its chemical characteristics, and its mineralogical peculiarities is undoubtedly important. Important also are the specific physical properties which arise because of textural and structural make-up, such as specific gravity, volume weight, pore space, and immense internal surface. These phases, however interesting in themselves, must not be studied so closely as to prevent their broad and vital plant correlations from becoming evident. None of the transformations concomitant with normal crop production takes place in the soil without definite and widespread cooperation. The study of the soil particle is, therefore, more than a consideration of a few interesting physical and chemical phenomena. From such investigations have been developed and perfected the broad principles which govern successful soil management and economical food production.

CHAPTER V

THE ORGANIC MATTER OF THE SOIL

One of the essential differences between a soil and a mass of rock fragments lies in the organic content of the former. Organic matter is necessary in order that mineral material may become a soil and that it may grow crops successfully. The physical condition of soils depends largely on the presence of organic matter and chemical reaction is greatly accelerated by its decay.

In the process of soil formation the addition of organic materials is more or less a secondary step. In residual debris the amount of organic matter held by the growing soil increases as the process of weathering goes on; in glacial soils, however, the matrix or skeleton of the soil is already formed before there is an opportunity for organic matter to become incorporated in it. The final result from the mixing of minerals and their weathered and altered products with the decayed or partially decayed organic matter that is sure to accumulate, is a mass much more complicated than either of the original constituents. The complexity of the average soil has already been sufficiently stressed.

54. The source of soil organic matter[1] and the character of plant tissue.—The source of practically all soil

[1] The soil organic matter includes not only all compounds contained in the original vegetable and animal tissues but also those existing in the partially decayed portions of such material. Carbon dioxide, methane and like compounds are usually not considered as a part of the soil organic matter. In this respect, the above definition is narrower than that for organic chemistry, which is the chemistry of carbon compounds. For a very good review of literature on soil organic matter, see Morrow, C. A., *The Organic Matter of the Soil: A Study of the Nitrogen Distribution in Different Soil Types;* Dissertation, Univ. Minn., 1918.

organic matter is plant issue.[1] Some of this matter accumulates from the above-ground parts of plants that have died and fallen down to become mixed with the surface soil; the remainder is a result of root extension and subsequent decay. The organic matter of the surface soil is derived from the tops and the roots of plants growing on it, while that of the subsoil is very largely a result of root extension and subsequent decomposition.

Since soil organic matter has its origin very largely from the higher plants, it is advisable to consider the general chemical nature of such material.[2] About 75 per cent. of average green plant tissue is water. The dry matter is made up of carbon, oxygen, hydrogen, and mineral material in the approximate ratio of 6, 5, 1 and 1 respectively. The preponderant elements of normal plant tissue are evidently carbon, oxygen, and hydrogen. (See Fig. 20.)

It is usual in classifying the compounds in plants to group them under the following heads: (1) carbohydrates, (2) fixed oils and waxes, (3) volatile oils and resins, (4) organic acids and their salts, and (5) nitrogenous compounds.[3] The

[1] It must not be inferred that higher plants are the only source of soil organic matter. Assuming that the weight of one bacterial cell is .000,000,002 of a milligram and that in each gram of a normal fertile soil, weighing 2,000,000 pounds to an acre-seven inches, there are 100,000,000 of such organisms, the weight of bacteria alone would be 400 pounds to the surface acre. This is a very conservative estimate, 800 pounds probably being more nearly correct. Considering the molds, fungi, algæ, actinomycetes, insects, and earthworms, there are probably 2000 pounds of living material in every acre of normal soil exclusive of plant roots. These organisms in their functioning supply no insignificant portion of the soil organic matter.

[2] For a fuller discussion see: Ingle, Herbert, *Manual of Agricultural Chemistry,* Chap. X, London, 1913. Also, Stoddard, C. W., *The Chemistry of Agriculture,* Chap. III, Philadelphia and New York, 1915. Also, Thatcher, R. W., *The Chemistry of Plant Life,* New York, 1921.

[3] I. Carbohydrates—Sugars, starch, cellulose, legnin, inulin, gums, pectins, and pentosans.

II. Fixed oils and waxes—Castor oil, corn oil, cottonseed oil, linseed oil, and the like.

III. Volatile oils and resins—Oil of mustard, of cloves, of peppermint, etc. Rosin, myrrh, balsam, etc.

mineral matter or so-called ash exists as a part of the compounds listed under these headings. The carbohydrates, having the general formula of $C_x(H_2O)_n$ include such compounds as starch, cellulose, dextrose, glucose, cane sugar, and the like. The fats and oils may be represented in plants by such glycerides as butyrin, stearin, olein, palmitin, while many acids of an organic nature exist especially in fruits and vegetables.

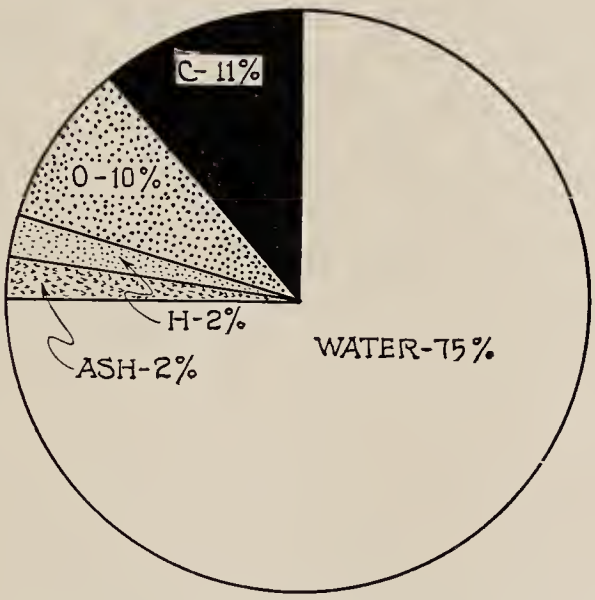


FIG. 20.—Diagram showing the general composition of green plant tissue. The nitrogen which is generally less than .5 per cent. is included with the ash in the above diagram. (After Stoddard.)

Of the five groups, however, the nitrogenous compounds are probably the most complicated as they carry not only carbon, hydrogen, oxygen, and nitrogen, but also mineral elements such as sulfur, phosphorus, calcium and iron. They are compounds of high molecular weight and many are of unknown

IV. Organic acids and their salts—Citric acid, malic acid, tannic acid, tartaric acid, and the like.

V. Nitrogenous compounds—Nitrates, ammonia, amides, amino-acids, alkaloids, and proteins.

constitution. Simple proteins, such as albumin, globulin, protamins, and others, are found in plants, besides certain derived proteins such as proteosis and peptones. In addition to all these, there is a host of other nitrogenous compounds that have no small influence on the composition of the soil organic matter.[1]

It is also necessary to consider that certain portions of the cell contents and cell walls are in a collodial state. Such a condition is important as the translocation of dissolved substances from soil to plant and from cell to cell depend largely on their diffusibility through colloidal membranes.

It is evident even from this brief discussion that the chemical character of plant tissue is far from simple. The degradation of such material, especially in the presence of complex mineral products, generally gives rise at first to compounds no simpler; in fact, the chances are that the resulting compounds will be much more complicated. It is only later in the processes of decomposition that simple products result.

[1] Crops are usually analyzed for six constituents—water, ash, crude protein, crude fiber, nitrogen free extract, and crude fat. Water is determined by drying the sample at the temperature of boiling water. By burning a sample of the plant tissue until all of the organic matter has been driven off, the percentage of mineral matter may be found. Crude protein is obtained by mulptiplying the figure for total nitrogen by 6.25. Crude fat is found by extracting the dry plant tissue with ether, while the crude fiber is that which remains of the fat-free material after treatment with both dilute sulfuric acid and dilute sodium hydroxide solutions. Nitrogen-free extract is the difference between the sum of the above constituents and 100 per cent. Below are four typical analyses:

Crop	Water %	Ash %	Crude Protein %	Crude Fiber %	Nitrogen Free Extract %	Crude Fat %
Alfalfa (green) ...	71.8	2.7	4.8	7.4	12.3	1.0
Lettuce (fresh) ...	94.7	.9	1.2	.7	2.2	.3
Wheat (grain)	10.5	1.8	11.9	1.8	71.9	2.1
Timothy (hay)	13.2	4.4	5.9	29.0	45.0	2.5

55. Decomposition[1] of organic matter in soils.—While the general trend of organic degradation in soils is towards simplification, the process is by no means a progressive one. Many products are built up that are much more complex than the original tissue. Most of the fermentation and putrefaction is due to that great group of organisms called bacteria, although molds, fungi, and the like also are important. The action of these organisms may be direct, but is more likely to be enzymic.[2] A cycle is therefore set up, in which the higher plants and animals are occupied in building up, while bacteria are tearing down and reducing the residue of plant action to simple forms, such as can be ultimately utilized again in plant nutrition. The importance of soil organisms is thus evident, and the encouragement of their growth and function is clearly a part of good soil management. (See Fig. 21.)

When the complex molecules that make up plant tissue break down, they split along definite lines of cleavage, depending on the structure of the original molecule. These bodies, which are usually simpler in nature than those from which they have sprung, are called cleavage products, and without a doubt their appearance is the first step in organic decomposition. These compounds are subject to still further change, and because of the great number of agencies at work the secondary products that result may be simpler or more complex, according to conditions. Some bacteria have a tendency, while tearing down organic matter, to produce synthetic compounds, which present a very complicated molecule until they are in turn degraded. The tendency for the secondary products to react both among themselves and with the

[1] Decomposition and decay are general terms referring to all of the degradation processes through which the original tissue passes in the soil. Fermentation refers to the decomposition of carbohydrates while putrefaction has to do usually with nitrogenous materials.

[2] A catalytic agent is a material capable of hastening or retarding a chemical reaction, the catalyst emerging unchanged from the transformation. Enzymes are catalysts produced by living organisms and may be active within or without the cell. They are generally colloidal in nature.

mineral constituents is by no means an unimportant factor in accounting for the complexity of the decaying organic matter.

As the processes of fermentation and putrefaction go on the complex intermediate compounds are gradually broken down and certain simple products result. Such materials may result from a progressive simplification of the partially de-

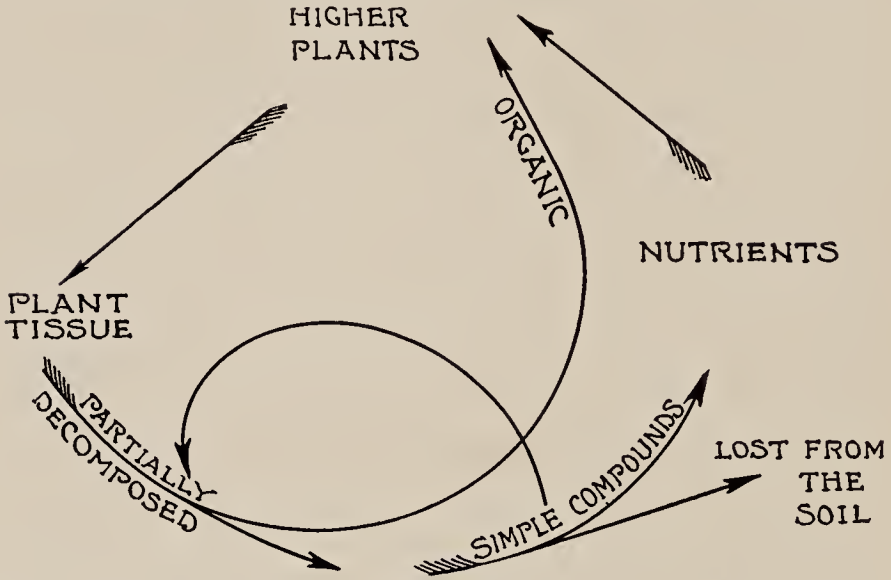


FIG. 21.—Diagram showing the transformations through which the constituents of the plant tissue pass from the time the organic matter enters the soil until it is in a condition to be used by succeeding crops. The cycle is very largely biological.

cayed matter or may be by-products or split-off compounds from the more complex reactions. These simple materials are partially solid and partially gaseous. Carbon dioxide is a universal product of bacterial activity of all kinds and is constantly being evolved. Other simple constituents arising from organic decay are water, ammonia, nitrites, nitrates, free nitrogen, and sulfur dioxide. Some of these are lost from the soil, some lose their identity by reacting with the soil constituents, while others may function as plant nutrients. When

they are absorbed again by a crop, the organic cycle is completed.

56. The partially decomposed organic matter.[1]—The most complicated parts of the organic matter in the soil are the primary and secondary products of decomposition, the materials between the original tissue and the simple products. These compounds are not only complex but they are continually changing. A certain compound present in the soil one week may be altered the next. Again, at least a part of the decomposing organic matter is colloidal, thus possessing special absorptive and catalytic properties. When the soil organic matter is treated with the various extractive agents, reactions may be induced which would not take place in a normal soil. Compounds are then formed which would probably not exist under natural conditions.

Many chemists have worked on the problems of the constitution of the organic matter of the soil and have published their results. The early conceptions were rather simple. Mulder,[2] for example, considered the soil organic matter to consist almost entirely of carbon, hydrogen, and oxygen. Such a concept ignores the presence of nitrogen, sulfur, and the mineral elements of the original plant tissue, and is much too simple to explain organic transformations.

Even the investigators[3] of Mulder's time obtained discor-

[1] See Morrow, C. A., *The Organic Matter of the Soil; A Study of the Nitrogen Distribution in Different Soil Types;* Dissertation, Univ. Minn., 1918.

[2] Mulder, T. J., *Die Organischen Bestandtheile im Boden;* Chemie der Ackerkrume, I, pp. 308-360, Berlin, 1863. Also, Wiley, H. W., *Agricultural Analysis;* Vol. I, p. 53, Easton, Pa., 1906.

Mulder contended that the organic matter consisted of seven distinct compounds, as follows: 1 & 2, Ulmic acid and ulmin; 3 & 4, Humic acid and humin; 5, Geic acid; 6, Apocrenic acid; 7, Crenic acid. These bodies he considered as arising from one another by oxidation; thus ulmic acid ($C_{40}H_{14}O_{12}$) gave humic acid ($C_{40}H_{12}O_{12}$), which in turn yielded geic acid ($C_{40}H_{12}O_{14}$), followed by apocrenic acid ($C_{48}H_{12}O_{24}$), and finally by crenic acid ($C_{24}H_{12}O_{18}$).

[3] See Schreiner, O., and Shorey, E. C., *The Isolation of Harmful Organic Substances from Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 53, pp. 15-16, 1909.

dant results, but these were explained for the time being by assuming that the discrepancies occurred because of added molecules of water.

Later investigators, while progressing rather slowly toward definite results, did accomplish one thing of importance. They threw considerable doubt on the old ideas of the Mulder school of chemists.

One of the men, whose work established beyond a doubt the fact that organic matter was a mixture of very complicated compounds, was Van Bemmelen.[1] His investigations still further showed that the soil organic matter was largely in a colloidal condition, and, therefore, exhibited properties quite distinct from those shown by true solutions or matter in a coarse state of division.

In recent years, Baumann[2] by his researches has shown freshly precipitated organic matter to possess properties which are largely colloidal in nature. Among these characteristics are high water capacity, great absorptive power for certain salts, ready mixture with other colloids, power to decompose salts, great shrinkage on drying, and coagulation in the presence of electrolytes. Jodidi[3] has studied the composition of the acid-soluble organic nitrogen in peat and mineral soils. The nitrogenous compounds thus obtained can be divided into the following groups: (1) ammoniacal nitrogen, (2) nitric nitrogen, (3) acids amides, (4) mon- and diamino-acids. The two latter groups[4] carry the bulk of the organic nitrogen,

[1] Van Bemmelen, J. M., *Die Absorptions Verbindungen und das Absorptionsvermögen der Ackererde;* Landw. Versuch. Stat., Band 35, Seite 67-136, 1888.

[2] Baumann, A., *Untersuchungen Über die Hummussäuren;* Mitt. d. K. bayr. Moorkulturanstalt, Heft 3, Seite 53-123, 1909.

[3] Jodidi, S. L., *Organic Nitrogenous Compounds in Peat Soils I;* Mich. Agr. Exp. Sta., Tech. Bul. 4, Nov., 1909. Also, *The Chemical Nature of the Organic Nitrogen in Soil;* Ia. Agr. Exp. Sta., Res. Bul. I, June 1911.

[4] Amides or acid amides are formed from organic acids by replacing the hydroxyl of the carboxyl group with NH_2. Acetic acid (CH_3COOH)

but quantitative determinations are uncertain. These compounds produce ammonia readily, the rate depending on their chemical structure.

The present knowledge of the chemical constitution of the soil organic matter is due largely to investigations prosecuted by the United States Bureau of Soils.[1] As a result of several years work a large number of compounds were isolated. Some are original constituents of the plant tissue but the bulk has arisen through the process of organic decomposition.

The compounds isolated were classified from the chemical standpoint under four heads, those containing: (1) carbon and hydrogen; (2) carbon, hydrogen, and oxygen; (3) carbon, hydrogen, and nitrogen, or carbon, hydrogen, oxygen, and nitrogen; (4) sulfur in combination with any or all of the elements listed above. With the possible presence in soils of compounds containing so many elements, it is little wonder that the subject is a complicated one. It is evident, moreover, that any list now available will be only partial, and that many other compounds of even more intricate composition will be isolated later.

A list of some of the compounds isolated from soil organic matter by the Bureau of Soils follows:

thus becomes acet-amide (CH_3CONH_2). Amino-acids are produced by replacing one of the alkyl hydrogens with NH_2. Acetic acid thereby becomes amino-acetic acid or glycocoll ($CH_2(NH_2)COOH$). Protein hydrolysis is probably as follows:

$$\text{Proteins} \longrightarrow \text{Proteoses} \longrightarrow \text{Peptones} \longrightarrow \text{Peptides} \begin{cases} \nearrow \text{Acid amides} \\ \searrow \text{Amino-acids} \end{cases}$$

[1] Schreiner, O. and Shorey, E. C., *The Isolation of Harmful Substances from Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 53, 1909; also Buls. 47, 70, 74, 77, 80, 83, 87, 88, and 90. See also, Sullivan, M. X., *Origin of Vanillin in Soil;* Jour. Ind. & Eng. Chem., Vol. 6, No. 11, pp. 919-921, 1914. Kelley, W. P., *The Organic Nitrogen of Hawaiian Soils;* Jour. Amer. Chem. Soc., Vol. XXXVI, No. 2, pp. 429-444, Feb., 1914. Walters, E. H., *Proteoses and Peptones in Soils;* Jour. Ind. & Eng. Chem., Vol. 7, No. 10, pp. 860-863, 1915. Lathrop, E. C., *Protein Decomposition in Soils;* Soil Sci., Vol. I, No. 6, pp. 509-532, June, 1916.

Hentriacontane—$C_{31}H_{64}$
Dihydroxystearic acid—$C_{18}H_{36}O_4$
Succinic acid—$C_4H_6O_4$
Picoline carboxylic acid—$C_7H_7O_2N$
Histidine—$C_6H_9O_2N_3$
Trithiolbenzaldehyde—$(C_6H_3CSH)_3$
Creatinine—$C_4H_7ON_3$
Salicylic Aldehyde—C_6H_4OHCOH

57. Relation of organic compounds to plants.—So far as the plant is concerned, organic compounds may be divided into three groups: those that are beneficial, those that are neutral, and those that are toxic or harmful in their effects. As an example of the first group, histidine and creatinine [1] may be mentioned. Here is a case in which the compounds in the soil organic matter may exert a stimulating effect on plant growth, supplementing the nitrates [2] to a certain extent. That the nitrogen of the soil organic matter may be utilized by plants is well summarized by the publications of Hutchinson and Miller.[3] As an example of a harmful compound arising from the decomposition of the organic matter, dihydroxystearic acid may be mentioned as one of the best known. This compound was the first to be isolated and identified by the Bureau of Soils and is very toxic.

The discovery of such compounds in the soil has revived the old theory of toxicity,[4] by which the infertility of certain soils was accounted for. Root excretions were also held to be detrimental to succeeding crops of the same kind. The toxic materials of the soil organic matter largely originate under

[1] Skinner, J. J., *Effect of Histidine and Arginine as Soil Constituents;* Eighth Internat. Cong. App. Chem., Vol. XV, pp. 253-264, 1912. Also, *Beneficial Effects of Creatinine and Creatine on Growth;* Bot. Gaz., Vol. 54, No. 2, pp. 152-163, 1912.

[2] Schreiner, O., and Skinner, J. J., *Nitrogenous Soil Constituents and Their Bearing upon Soil Fertility;* U. S. Dept. Agr., Bur. Soils, Bul. 87, p. 68, 1912. Also, Schreiner, O., and Others, *A Beneficial Organic Constituent of Soils; Creatinine;* U. S. Dept. Agr., Bur. Soils, Bul. 83, p. 44, 1911.

[3] Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Jour. Agr. Sci., Vol. 4, Part 3, pp. 282-302, 1912.

[4] See Schreiner, O., and Reed, H. S., *Some Factors Influencing Soil Fertility;* U. S. Dept. Agr., Bur. Soils, Bul. 40, pp. 36-40, 1907.

conditions of poor drainage and aëration. The toxicity of such compounds as dihydroxystearic acid, picoline carboxylic acid and aldehydes may, therefore, be overcome by oxidation.[1] Good soil aëration is a factor in dealing with such conditions.

Fertilizers, according to Schreiner and Skinner,[2] seem to decrease the harmful effects of such compounds; nitrogenous fertilizers overcoming some toxic materials, and phosphoric acid or potash neutralizing others. Robbins [3] has shown that soil organisms have the power of causing the disappearance of certain toxic materials in the soil, such as cumarin, vanillin, pyridine, and quinoline.

While Schreiner found twenty soils, out of a group of sixty taken in eleven states of this country, to contain dihydroxystearic acid, this does not necessarily mean that this or similar compounds are serious detrimental factors. It is very likely that such compounds are merely products of improper soil conditions, and are to be considered as concomitant with depressed crop yield. When such conditions are righted, the so-called toxic matter will disappear, as has been shown by the researches of Davidson.[4] Good drainage, lime, tillage, aëration, and oxidation, are so efficacious in this regard that permanent organic soil toxicity need never be a factor in soils rationally managed.

[1] Schreiner, O., and Others, *Certain Organic Constituents of Soils in Relation to Soil Fertility;* U. S. Dept. Agr., Bur. Soils, Bul. 47, p. 52, 1907. Also, Schreiner, O., and Reed, H. S., *The Role of Oxidation in Soil Fertility;* U. S. Dept. Agr., Bur. Soils, Bul. 56, p. 52, 1906.

[2] Schreiner, O., and Skinner, J. J., *Organic Compounds and Fertilizer Action;* U. S. Dept. Agr., Bur. Soils, Bul. 77, 1911. Also, *Experimental Study of the Effect of Some of the Nitrogenous Soil Constituents on Growth;* Plant World, Vol. 16, No. 2, pp. 45-60, Feb., 1913.

[3] Robbins, W. J., *The Cause of the Disappearance of Cumarin, Vanillin, Pyridine and Quinoline in the Soil;* Ala. Agr. Exp. Sta., Bul. 195, June, 1917. Also, *The Destruction of Vanillin in the Soil by the Action of Soil Bacteria;* Ala. Agr. Exp. Sta., Bul. 204, June, 1918. Robbins, W. J., and Massey, A. B., *The Effect of Certain Environmental Conditions on the Rate of Destruction of Vanillin by a Soil Bacterium;* Soil Sci., Vol. X, No. 3, pp. 237-246, Sept., 1920.

[4] Davidson, J., *A Comparative Study of the Effects of Cumarin and Vanillin on Wheat Grown in Soil, Sand and Water Culture;* Jour. Amer. Soc. Agron., Vol. 7, No. 4, pp. 145-158, 1915.

58. Simple products of organic decomposition.—As the processes of chemical and biological change of the soil organic matter proceed, the simple compounds already noted begin to appear. This change is of course coördinate with a certain amount of synthetic action, but compounds thus built up must ultimately succumb to the agencies at work and suffer a splitting-up and reduction to simple bodies. Carbon dioxide is one of the most important of these compounds, always being a product of bacterial activity. Its importance has already been noted in the discussion of weathering. Here it heightens the solvent power of water and tends to increase the amount of nutrient material carried in the soil solution. Carbonation is a direct result of its presence.

With increased organic matter in any soil, greater bacterial action and an increase in the carbon dioxide evolved may well be expected. In fact, the carbon dioxide production of a soil is considered by some authors [1] to be a measure of bacterial activity. With this increase in carbon dioxide, the soil air is markedly reduced in its free oxygen and an alteration in bacterial and plant relationships may thereby be induced. The following figures by Wollny [2] show the composition of the soil atmosphere and the effects of additional organic material on the carbon dioxide content:

TABLE XXI

SOILS	PERCENTAGE BY VOLUME OF	
	CO_2	O
Atmospheric air	.04	20.96
Soil air (average 19 analyses)	2.54	18.33
A sandy soil	1.06	19.72
Sandy soil plus manure	9.74	10.35

[1] Stoklasa, J., and Ernest, A., *Über den Ursprung, die Menge, und die Bedeutung des Kohlendioxyds im Boden;* Centrlb. Bakt., II, 14, Seite 723-736, 1905.

[2] Wollny, E., *Die Zersetzung der Organischen Stoffe;* Seite 2, Heidelberg, 1897.

While carbon dioxide may be evolved by the splitting-up of both carbohydrate and nitrogenous bodies, ammonia results only from the latter. It is really the first extremely simple nitrogenous body produced. It can be utilized by some plants as a source of nitrogen, as is also true of certain products of partial decomposition such as urea, but ordinarily it must undergo oxidation. This oxidation results in nitrites (NO_2) and ultimately in nitrates (NO_3), the latter usually being considered as the chief source of the nitrogen utilized by plants.

Other simple products, such as methane (CH_4), hydrogen disulphide (H_2S), carbon disulphide (CS_2), and the like, may also result. They are relatively unimportant, however, as regards the plant, in comparison with the rôle played by carbon dioxide, ammonia, the nitrites, and the nitrates. The production of the nitrates from ammonia is very closely correlated with good soil conditions, especially optimum moisture and adequate aëration. The proper handling of the soil, then, will not only tend to eliminate toxic matter and prevent its further formation but will encourage the proper decay of the soil organic matter and the production of simple compounds which will function directly or indirectly as nutrients.

59. Carbonized materials of soil.—After the extraction of the soil for the study of the ordinary organic compounds, a considerable mass of material remains, which is insoluble in water, alkali, and other ordinary solvents. By the extraction of a large amount of soil, Schreiner and Brown [1] were able to study this material. They found it susceptible to division into six groups, as follows: (1) plant tissue, (2) insect and other organized material, (3) charcoal particles, (4) lignite, (5) coal particles, and (6) materials resembling natural hydrocarbons, as bitumen, asphalt, and the like. Such ma-

[1] Schreiner, O., and Brown, B. E., *Occurrence and Nature of Carbonized Material in Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 90, 1912.

terial was found not only near the surface of the soil but at depths of fifteen or twenty feet.

The exact origin of this material is problematical. Forest and prairie fires, infiltration, mild oxidation, and lignification might be mentioned. Of a certainty the agencies of distribution are the natural forces engaged in physical weathering. Such material can be divided into two general groups, organized and unorganized; in the former, the normal structure remains intact, while in the latter the original features have been obliterated. Part of it belongs, therefore, in the original plant tissue group; a part of it with the partially decayed material; while some must be included with the simple products of decomposition. This carbonized material is important, as it makes up no inconsiderable part of the soil organic matter. It is very resistant, and consequently lends stability to the organic constituents.

60. The determination of soil organic matter.[1]—A number of methods have been proposed for the direct or indirect determination of the organic matter in soils, but none has proved entirely satisfactory, since the composition of this material is so indefinite and complicated and so likely to change while under investigation. Other soil constituents also tend to interfere with the determination. Three general methods seem worthy of mention, as they have been used very widely in soil analyses and at least give comparative, if not absolutely accurate, results. They will be discussed in the inverse order of their value.

Loss of ignition.[2]—This is a simple method which designs to burn off the organic matter and determine its loss by difference. Five grams of dry soil are placed in a crucible and ignited at a low red heat until the organic matter is all oxi-

[1] Soil organic matter as here used refers only to the original and partially decayed organic constituents. Carbon dioxide, methane, nitrites, nitrates and similar compounds are, therefore, not included in this term.

[2] Wiley, H. W., *Official and Provisional Methods of Analysis;* U. S. Dept. Agr., Bur. Chem., Bul. 107, p. 19, 1908.

dized. The cold mass is moistened with ammonium carbonate and heated to a temperature of 150°C. in order to expel the excess of ammonia and replace the carbon dioxide. The change in weight is rated as loss on ignition.

This method is open to the objection that, besides the loss of organic matter, a certain amount of water of combination, and all ammoniacal compounds, nitrates, carbon dioxide, and some alkali chlorides, if the temperature is carried too high, are driven off. The method, therefore, gives high results, especially in the presence of large amounts of hydrated silicates such as are likely to occur in residual soils. Notwithstanding these objections, this method has been used to a very great extent in soil analysis.[1]

Chromic acid method.—This method, proposed by Wolff, has been modified and improved by various chemists. Warington and Peake [2] have perhaps done more with the method than any other investigators. In the United States the modification by Cameron and Breazeale [3] has been very generally accepted.[4] It consists in the treatment of the soil sample with sulfuric acid, and chromic acid, or potassium bichromate. The organic matter, in the presence of the sulfuric acid and an oxidizing agent, evolves carbon dioxide until, if the mix-

[1] Rather offers a modification to this method which seems to obviate some of its difficulties. The soil is first extracted with dilute HCl and HF to remove the hydrated aluminum silicates, the organic matter being little influenced thereby. The sample is then ignited in the usual manner. Rather, J. B., *An Accurate Loss-on-Ignition Method for the Determination of Organic Matter in Soils;* Jour. Ind. and Eng. Chem., Vol. X, No. 6, pp. 439-442, June, 1918.

[2] Warington, R., and Peake, W. A., *On the Determination of Carbon in Soils;* Jour. Chem. Soc. (London), Trans., Vol. 37, pp. 617-625, 1880.

[3] Briggs, L. J., and others, *The Centrifugal Methods of Mechanical Soil Analysis;* U. S. Dept. Agr., Bur. Soils, Bul. 24, pp. 33-38, 1904. Also, Cameron, F. K., and Breazeale, J. F., *The Organic Matter in Soils and Subsoils;* Jour. Amer. Chem. Soc., Vol. 26, pp. 29-45, 1904.

[4] Waynick offers a simplification of this method: Waynick, D. D., *A Simplified Wet Combustion Method for the Determination of Carbon in Soils;* Jour. Ind. and Eng. Chem., Vol. XI, No. 7, pp. 634-637, 1919.

ture is boiled, practically all of the carbon is thus driven off. This gas is drawn through a train of absorption bulbs, caught in a solution of potassium hydroxide, and thus weighed.

A second determination is now made on a new sample of soil, leaving out the chromic acid. The carbon dioxide given off under such conditions is that of an inorganic nature. The weight of this gas substracted from the total carbon dioxide leaves the organic carbon dioxide.

The data from the use of the chromic acid method may be expressed as organic carbon or as organic matter. Multiplying the carbon dioxide by .471 or the carbon by 1.724 is considered as giving an approximate figure for the organic matter.

The results obtained with the chromic acid method are usually lower than those from ignition or combustion, due partially to the oxidation resistance of the carbonized matter, already discussed. This material, while it succumbs to ignition, resists the action of the sulfuric and chromic acids to a very large degree. The water of hydration is, of course, not a factor in the chromic acid method.

Bomb Combustion.[1]—Two grams of soil, .75 gram of magnesium powder, and 10 grams of sodium peroxide (Na_2O_2) are thoroughly mixed in a closed dry calorimeter bomb. The mixture is then exploded by heating, all of the carbon of the soil being changed to the carbonate form by the reaction. The fused charge is now removed to a flask and by treating with acid, the carbon in the form of carbon dioxide may be driven off into a Parr apparatus and measured under standard conditions of temperature and pressure.

The amount of inorganic carbonate carbon in the soil must

[1] Wiley, H. W., *Official and Provisional Methods of Analysis;* U. S. Dept. Agr., Bur. Chem., Bul. 107, p. 234, 1908.

There are a number of other methods of complete combustion. Very often the combustion is carried on in a current of oxygen over hot cuprous oxide. The organic carbon may thus be very accurately determined.

be determined on a separate sample and deducted from the figure obtained by the combustion above described. This will give the organic carbon of the soil in terms of carbon dioxide. The percentage of organic carbon may now be calculated as well as the approximate amount of organic matter ($C \times 1.724$ = organic matter or $CO_2 \times .471$ = organic matter.)[1]

61. Determination of soil humus.—Humus[2] is a term applied to that portion of the organic matter which can be removed with ammonium hydroxide after the soil has been treated with hydrochloric acid and washed free thereof. The common method of humus estimation is that proposed by Grandeau.[3] The sample of soil is first washed with acid in order to remove the bases in combination with the organic matter. It is next treated with ammonia, which will then dissolve out the humous materials. The method is based on the fact that when a soil is lacking in active basic material, certain parts of the organic matter are soluble in an alkali. The dark humous extract obtained with the ammonia is called Matière Noire and is supposed to be the most active part of the soil organic matter.

This method has undergone several modifications[4] of which

[1] Wiley presents the following comparisons of the three methods discussed above:

Soil	Ignition	Combustion (c × 1.724)	Chromic acid (c × 1.724)
Old pasture	9.27	6.12	4.84
New pasture	7.07	4.16	3.32
Arable soil	5.95	2.44	2.03

Wiley, H. W., *Principles and Practices of Agricultural Analysis*, Vol. 1, pp. 352-354, Easton, Pa., 1906.

[2] The term "humus" is used in a number of different ways. Continental Europeans make it synonymous with organic matter. In some cases it is used to indicate all of the partially decayed material of the soil. The restricted meaning employed in this text is less confusing as it coincides with the chemical interpretation. Grandeau believed the organic matter thus dissolved was a determining factor in soil fertility.

[3] Grandeau, L., *Traiti d'Analyse de Matières Agricoles;* I, p. 151, 1897.

[4] A comparison of the various methods is found as follows: Alway,

that of Hilgard [1] and that of Houston and McBride [2] seem most important.

In the procedure an attempt is made to keep the concentration of the ammonia in contact with the soil constant during the extraction. Consequently the sample, after treatment with the acid, is washed into a 500 cubic centimeter flask, which is filled to the mark with 4 per cent. ammonia. Digestion is allowed to proceed for twenty-four hours, with frequent shakings. The solution is then filtered and evaporated to dryness. The residue is weighed, after drying thoroughly at 100° C, and then ignited, the loss being considered as humus.

This method is open to serious criticism in that it is wholly arbitrary and subject to considerable inaccuracy through manipulation and the ignition of the humic residue. There is also some doubt whether the figures obtained have any direct relation to the fertility of the soil.[3]

62. The organic matter and nitrogen of representative soils.—The amount of organic matter in soils varies so widely according to the nature of the soil and climate conditions that it is difficult to present representative figures. Excluding peat and muck, which are 20 to 80 per cent. organic, the average mineral surface soil is found to contain from .50 per cent. to 18 or 20 per cent. of organic matter. Some surface soils of West Virginia,[4] averaging 2.88 per cent. organic matter,

F. J., and others, *The Determination of Humus;* Neb. Agr. Exp. Sta., Bul. 115, June, 1910.

[1] Hilgard, E. W., *Humus Determination in Soils;* U. S. Dept. Agr., Div. Chem., Bul. 38 (edited by H. W. Wiley), p. 80, 1893.

[2] Houston, H. A., and McBride, F. W., *A Modification of Grandeau's Method for the Determination of Humus;* U. S. Dept. Agr., Div. Chem., Bul. 38 (edited by H. W. Wiley), pp. 84-92, 1893. See also, Smith, O. C., *A Proposed Modification of the Official Method of Determining Humus;* Jour. Ind. and Eng. Chem., Vol. 5, No. 1, pp. 35-37, Jan., 1913.

[3] Gortner, R. A., *The Organic Matter of the Soil; III. On the Production of Humus from Manures;* Soil Sci., Vol. III, No. 1, pp. 1-8, Jan., 1917. Carr, R. H., *Is the Humus Content of the Soil a Guide to Fertility;* Soil Sci., Vol. III, No. 6, pp. 515-524, June, 1917.

[4] Salter, R. M., and Wells, C. F., *Analyses of West Virginia Soils;* W. Va. Agr. Exp. Sta., Bul. 168, Dec., 1918.

range from .73 per cent. to 15.14 per cent., while similar figures on the Russian Tschernozen [1] vary from 3.45 to 16.72 with an average of 8.07 per cent. The subsoil of course runs lower in every case. The following figures, while far from representative, are suggestive:

TABLE XXII

PERCENTAGE OF ORGANIC MATTER (C × 1.724) IN CERTAIN REPRESENTATIVE SOILS OF THE UNITED STATES.

DESCRIPTION	SURFACE	SUBSOIL
8 Residual soils—Robinson [2]	1.76	.64
3 Glacial and loessial soils—Robinson [2]	4.59	1.44
2 Kansas till soils—Call [3]	2.86	1.98
6 Nebraska loess soils—Alway [4]	3.83	1.96
30 Minnesota till soils—Rost and Alway [5]	7.46	1.88

As the soil nitrogen is carried almost wholly by the organic matter, and is a true organic constituent of the soil, its consideration at this point is opportune. The nitrogen [6] of soils varies with the organic matter and may range in surface mineral soils from .01 to .60 per cent. West Virginia [7] soils,

[1] Kossowitsch, P., *Die Schwarzerde;* Internat. Mitt. f. Bodenkunde, Band I, Heft 3-4, S. 316, 1912.

[2] Robinson, W. O., *The Inorganic Composition of Some Important American Soils;* U. S. Dept. Agr., Bul. 122, 1914.

[3] Call, L. E., *et al., Soil Survey of Shawnee County, Kansas;* Kans. Agr. Exp. Sta., Bul. 200, 1914.

[4] Alway, F. J., and McDole, G. R., *The Loess Soils of the Nebraska Portion of the Transition Region: I. Hygroscopicity, Nitrogen and Organic Carbon;* Soil Sci., Vol. I, No. 3, pp. 197-238, Mar., 1916.

[5] Rost., C. O., and Alway, F. J., *Minnesota Glacial Soil Studies;* I. *A Comparison of the Soils of the Late Wisconsin and Iowan Drifts;* Soil Sci., Vol. XI, No. 3, pp. 161-200, Mar., 1921.

[6] Soil nitrogen is determined by either the Kjeldahl or the Gunning method. These will be described later. See paragraph 165.

[7] Salter, R. M., and Wells, C. F., *Analyses of West Virginia Soils;* W. Va. Agr. Exp. Sta., Bul. 168, Dec., 1918.

for example, while averaging .147 per cent. nitrogen, range from .043 to .539. Louisiana [1] soils average .049 per cent. with a range from .001 to .109. In muck and peat the amount of nitrogen is much higher, attaining in some cases 3 per cent.

The following figures indicate the nitrogen contents that may be expected in average soils:

TABLE XXIII

PERCENTAGE OF NITROGEN IN CERTAIN REPRESENTATIVE SOILS OF THE UNITED STATES

DESCRIPTION	SOIL	SUBSOIL
71 Cecil soils of North Carolina [2]	.048	.024
165 Norfolk soils of North Carolina [3]	.039	.020
16 Loess soils of Central U. S.[4]	.154	.083
381 Kentucky soils [5]	.120	.070
30 Minnesota till soils [6]	.338	.092

While the ratio between the respective amounts of soil nitrogen and organic matter is no more constant than that between the organic carbon and the organic matter ($C \times 1.724 =$ organic matter), it is of some general value. If

[1] Walker, S. S., *Chemical Composition of Some Louisiana Soils as to Series and Texture;* La. Agr. Exp. Sta., Bul. 177, Aug., 1920.

[2] Williams, C. B., *et al., Report on the Piedmont Soils, Particularly with Reference to their Nature, Plant-food Requirements and Adaptability to Different Crops;* Bul. N. C. Dept. Agr., Vol. 36, No. 2, Feb., 1915.

[3] Williams, C. B., *et al., Report on Coastal Plain Soils, Particularly with Reference to their Nature, Plant-food Requirements and Suitability for Different Crops;* Bul. N. C. Dept. Agr., Vol. 39, No. 5, May, 1918.

[4] Robinson, W. O., *et al., Variation in the Chemical Composition of Soils;* U. S. Dept. Agr., Bul. 551, June, 1917. Alway, F. J., and McDole, G. R., *The Loess Soils of the Nebraska Portion of the Transition Region: I. Hygroscopicity, Nitrogen and Organic Carbon;* Soil Sci., Vol. I, No. 3, pp. 197-238, Mar., 1916. Also, Bennett, H. H., *Soils and Agriculture of the Southern States,* pp. 332-353; New York, 1921.

[5] Averitt, S. D., *The Soils of Kentucky;* Ky. Agr. Exp. Sta., Bul. 193, July, 1915.

[6] Rost, C. O., and Alway, F. J., *Minnesota Glacial Soil Studies: I. A Comparison of the Soils of the Late Wisconsin and the Iowan Drifts;* Soil Sci., Vol. XI, No. 3, pp. 161-200, Mar., 1921.

the percentage of nitrogen in the soil is multiplied by 20, a rough idea of the amount of organic matter may be obtained ($N \times 20 =$ organic matter). The following data from Rost and Alway[1] illustrate not only the variations in organic matter and nitrogen that may be expected in the surface and subsurface of different soils, but the correlation between the organic matter and nitrogen just mentioned:

TABLE XXIV

AVERAGE PERCENTAGE OF ORGANIC MATTER ($C \times 1.724$) AND NITROGEN IN THIRTY REPRESENTATIVE MINNESOTA TILL SOILS FROM THREE SERIES. THE FIGURES FOR EACH OF THE THREE SOIL TYPES ARE AVERAGES OF TEN ANALYSES.

Depth	Forest Carrington Loam		Upland Prairie Carrington Silt Loam		Lowland Prairie Fargo Silt Loam	
	Organic Matter	Nitrogen	Organic Matter	Nitrogen	Organic Matter	Nitrogen
1— 6 inches...	5.34	.253	7.96	.373	13.08	.616
7—12 "	2.41	.119	6.00	.285	8.00	.385
13—24 "	1.38	.078	3.11	.165	3.24	.150
25—36 "	.86	.041	1.31	.062	1.39	.054

The following tentative classification of mineral soils on the basis of their percentages of organic matter and nitrogen is offered for generalized field use:

TABLE XXV

Description	Percentage of Organic Matter	Percentage of Nitrogen
Low.....	.0— 3.0	.00— .10
Medium	3.0— 6.0	.10— .25
High.....	6.0—10.0	.25— .40
Very high.....	above 10.0	above .40

[1] Rost, C. O., and Alway, F. J., *Minnesota Glacial Soil Studies: I. A Comparison of the Soils of the Late Wisconsin and the Iowan Drifts;* Soil Sci., Vol. XI, No. 3, pp. 161-200, Mar., 1921.

63. The humus content of soils is of course lower than the organic matter contained in them. It likewise varies according to climate and region, not only in amount, but also in composition. The following data from Hilgard [1] and Alway [2] illustrate these points:

TABLE XXVI

THE COMPOSITION OF CALIFORNIA ARID AND HUMID SOILS. (HILGARD)

DESCRIPTION	HUMUS IN SOIL (Percentage)	NITROGEN IN HUMUS (Percentage)	NITROGEN IN SOIL (Percentage)
41 Arid uplands soils.....	.91	15.23	.135
15 Subirrigated arid soils..	1.06	8.38	.099
24 Humid soils.....	4.58	4.23	.166

TABLE XXVII

COMPARATIVE COMPOSITION OF SEMI-ARID (WAUNETA) AND HUMID (WEEPING WATER) LOESS SOILS OF NEBRASKA. (ALWAY)

DEPTH	ORGANIC MATTER (Percentage)		HUMUS (Percentage)		NITROGEN (Percentage)	
	WAUNETA	WEEPING WATER	WAUNETA	WEEPING WATER	WAUNETA	WEEPING WATER
1st foot.	2.77	4.98	1.02	2.34	.136	.236
2nd "..	1.38	3.02	.65	1.29	.082	.154
3rd "...	1.09	1.38	.48	.55	.065	.083
4th "...	.79	.83	.34	.27	.046	.059
5th "...	.55	.45	.26	.23	.038	.043
6th "...	.45	.36	.26	.19	.030	.038

[1] Hilgard, E. W., *Soils,* pp. 136-137; New York, 1911. For further data regarding Hilgard's conclusions see: Alway, F. J., and Bishop, E. S., *Nitrogen Content of the Humus of Arid Soils;* Jour. Agr. Res., Vol. 5, No. 20, pp. 909-916, Feb., 1916.

[2] Alway, F. J., *et al., The Loess Soils of the Nebraska Portion of the Transition Region: I. Hygroscopicity, Nitrogen and Organic Carbon;* Soil Sci., Vol. I, No. 3, pp. 197-238, Mar., 1916. *II. Humus, Humus-Nitrogen and Color;* Soil Sci., Vol. I, No. 3, pp. 239-258, Mar., 1916.

It is evident that humid soils not only contain the greater amounts of organic matter, but also excel in humus. The humus of the arid regions, however, is richer in nitrogen, due to the character of the decomposition going on. As a consequence the nitrogen in the soil of humid regions is not greatly in excess of that in the soils of drier climates. The percentage of humus not only decreases in the lower depths of the soil, but also changes in composition, becoming poorer in nitrogen the deeper the soil.

64. The influence of organic matter on the soil.—The effects of organic matter on soil and plant conditions are as numerous as they are complex. Some of the influences are direct, others are indirect. As the specific gravity of organic matter is low, the first effect of its addition would be to lower the specific gravity of the soil. The organic matter tends also to spread the individual particles of soil farther apart, especially in a clay. Such action will markedly influence the volume weight.

The loosening effects of organic matter are especially apparent in such soil as clay. On the other hand, because organic matter has a higher cohesive and adhesive power than sand, it performs the function of a binding material with the latter soil, a condition much to be desired in a material possessing such loose structure.

As the water capacity of organic matter is very high, a soil rich in organic constituents usually possesses a high water-holding power. This makes possible greater volume changes both on drying and in the presence of excessive moisture. The granulating effects of wetting and drying and freezing and thawing are, therefore, accelerated. The increased water capacity of the soil, resulting from the presence of organic materials, is of great importance in drought resistance, while the black color imparted by the humus tends to raise the heat absorptive power of the soil.

The better tilth induced by the presence of organic matter

in any soil tends to facilitate ease in drainage and to encourage good aëration. These two conditions are of course necessary for the promotion of soil sanitation. Root extension and bacterial activity are thus increased. It is of especial importance that the splitting-up of the organic matter shall take place in the presence of plenty of oxygen, in order that toxic compounds may not be generated and that products highly favorable to plant growth should be formed.

The soil organic matter, however, functions in other ways than those strictly physical and chemical. Its degradation products may serve as nutrients for higher plants. Bacteria and other soil organisms are also furnished a source of energy thereby and the production of carbon dioxide is much increased. This carbon dioxide, as well as the organic acids generated, tends to raise the capacity of the soil-water as a solvent, and thus the amount of mineral material available to the crop is greatly increased. The general effect of organic matter, then, is to better the soil as a foothold for plants, and to increase either directly or indirectly the available nutrient supply for the crop.

65. Maintenance of soil organic matter.[1]—The maintenance of a proper supply of organic matter in a soil is a question of great practical importance, as productivity is governed very largely by the organic content of the soil. This maintenance of the soil organic matter depends on two factors: (1) the source of supply and methods of addition; and (2) the promotion of proper soil conditions in order that the

[1] Snyder, H., *Effect of the Rotation of Crops upon the Humus Content and the Fertility of Soils;* Minn. Agr. Exp. Sta. Bul. 53, June, 1897. *The Production of Humus in Soils;* Minn. Agr. Exp. Sta., Bul. 89, Jan., 1905. Morse, F. W., *Humus in New Hampshire Soils;* N. H. Agr. Exp. Sta., Bul. 138, June, 1908. Hopkins, C. G., *Phosphorus and Humus in Relation to Illinois Soils;* Ill. Agr. Exp. Sta., Circ. 116. Feb., 1908. Thatcher, R. W., *The Nitrogen and Humus Problem of Dry Farming;* Wash. Agr. Exp. Sta., Bul. 105, June, 1912. Fippin, E. O., *Nature, Effects and Maintenance of Humus in the Soil;* Cornell Reading Course for the Farm, Vol. III, No. 50, Oct., 1913. Loughridge, R. H., *Humus of California Soils;* Calif. Agr. Exp. Sta., Bul. 242, Jan., 1914.

organic matter may perform its legitimate functions. The source of supply will be considered first.

The organic matter of the soil may be increased in a natural way by the plowing under of green crops. This is called green-manuring and is a very satisfactory practice. Such crops as rye, buckwheat, clover, peas, beans, and vetch lend themselves to this method of soil improvement. Not only do these crops increase the actual organic content of a soil, but in the case of legumes the nitrogen may also be increased in amount, if the nodule bacteria are present and active.

Green-manures to be effective must be hardy, rapid in growth, succulent, and should produce abundant foliage. Rye and oats are particularly valuable from this standpoint. Such legumes as cowpeas, vetch, field peas, soybeans, and velvet beans are adapted to summer growth. Red clover or sweet clover, being a biennial, may be seeded one year and turned under the next spring. Oats and peas or rye and peas make a very good combination for fall green-manuring. Hairy or winter vetch may be seeded with rye in the autumn and used as a green-manure in the spring. In the South green-manuring crops may be utilized to much better advantage than in the northern states as the longer growing season permits the use of a green-manure following the normal harvest.

Due to the tendency of bare soil to lose nutrients by leaching, especially in the summer and fall, it is always best to keep the land covered with vegetation of some kind. Cover- or catch-crops are used for this purpose, especially on sandy land, although they are profitable on heavier soils as well. Wheat on sandy land may be followed by cowpeas, which not only conserve nitrates but fix nitrogen from the air in addition. Rape, cowpeas, vetch, and soybeans are sometimes seeded in corn at the last cultivation. When a soil receives clean cultivation a part of the year, as is practiced very frequently in orchards, it is very desirable that a crop be plowed under oc-

casionally to replace the organic matter lost by oxidation. Whether such catch-crops are pastured or turned under, they tend to increase the soil organic matter. Weeds, which spring up after the crop is harvested, are often valuable as cover- and catch-crops and when turned under aid in maintaining the organic content of the land.

Crop residues form no inconsiderable portion of the organic matter produced on the land. If such materials as straw, stubble, cornstalks, and the like are incorporated in the soil, much will be accomplished towards the upkeep of the organic matter. The burning of straw and cornstalks, especially in the Middle West, entails an enormous waste of carbon as well as of nitrogen. The value of crop residues has been demonstrated very conclusively by the Illinois Experiment Station [1] on their outlying experimental farms. At Bloomington, for instance, the turning under of crop residues for five years increased the wheat yields 4.4, 7.9 and 5.9 bushels in 1911, 1912 and 1913 respectively.

Farm manure is one of the most important by-products on the farm and is especially valuable because of its organic matter. Although only about one-fourth of the organic materials of the original food given the animal ever reaches the land, the use of such a by-product is worth while, since the carbon it contains comes from the air and not from the soil. The main losses that the carbon of the crop undergoes when thus utilized are due to the digestive influences of the animal and to the leaching and fermentation which goes on in the manure. While sufficient manure ordinarily can not be produced from the crops grown on the farm to maintain the organic matter of its soil, the use of farm manure with green-manure and crop residues in a proper rotation is fundamental in good soil management.

66. Organic matter and soil conditions.—Improper soil

[1] Mosier, J. G., and Gustafson, A. F., *Soil Physics and Management*, p. 171; Philadelphia and London, 1917.

conditions not only prevent the proper decay of organic matter, but also tend to encourage the production of products inimical to plant growth. Therefore, in order that organic materials added to any soil may produce the proper decomposition products and perform their normal functions, soil conditions in general must be of the best. Tile drainage should be installed, if necessary, in order to promote aëration and

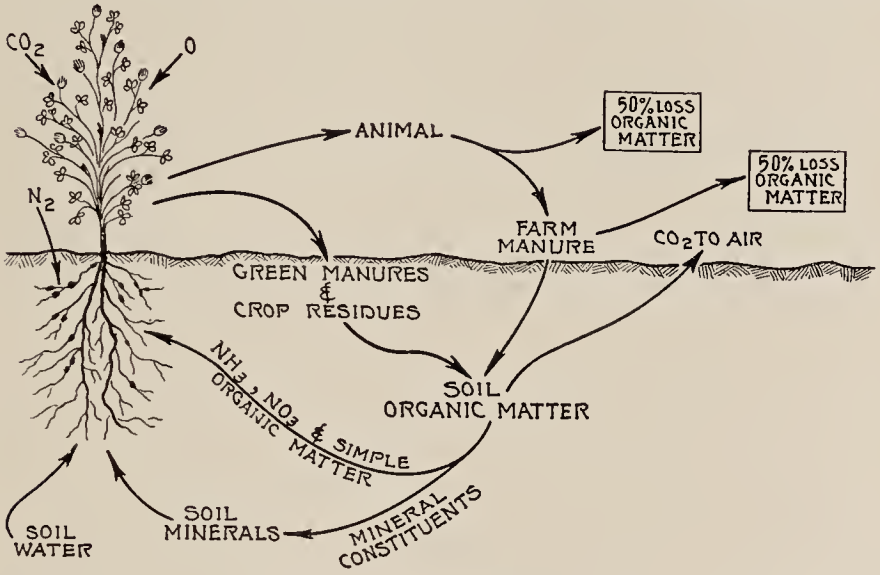


FIG. 22.—Diagram showing the practical sources of the soil organic matter and the cycle through which its constituents pass. Note that the carbon, oxygen and hydrogen come very largely from air and water and that fixation of nitrogen may occur if the crop is a legume. Only about 25 per cent. of the organic matter fed to animals ever reaches the soil in farm manure under average conditions.

granulation. Lime should be added if basic materials are lacking, for it promotes bacterial activity as well as plant growth. The addition of fertilizers will often be a benefit, as will also the establishment of a suitable rotation. The rotation of crops not only prevents the accumulation of toxic materials, but also, by increasing crop growth, makes possible a larger addition of organic matter by green-manuring.

67. Resume.—An understanding of the complex organic relationships within the soil is of great practical value, as it determines to a large degree the yield of crops, their rotation order and their fertilization. Moreover, tillage operations must be varied according to the organic nature of the soil. Unless a system of soil management is adopted which will at least partially keep up the organic matter of the soil, crop yields may be expected to decrease materially in a few years.

Good soil management seeks to adjust the addition of organic matter, the physical and chemical condition of the soil, and the losses through cropping and leaching, in such a way that paying crops may be harvested while impairing the organic supply of the soil as little as possible. Any system of agriculture that tends permanently to lower the organic matter of the land is impractical and improvident, as well as unscientific.

CHAPTER VI

THE COLLOIDAL MATTER OF THE SOIL[1]

RESEARCH in physics and physical chemistry is each day making it clearer that the properties of matter are by no means entirely determined by chemical composition. Matter varies in its physical character and its chemical activities with its fineness of division. Coarsely divided substances function much differently when they become molecular complexes and still more diversely when their aggregates are divided into their molecular and ionic components. Because of the particular properties exhibited by material in a fine state of division, approaching but not attaining a molecular simplification, a special name is utilized. A substance in such a condition is said to be colloidal or in the *colloidal state.*

68. The colloidal state[2] arises when one form of matter (either a gas, liquid, or solid) in a very fine state of division

[1] Colloidal chemistry is now so well understood that it will be necessary to develop only those phases which have a direct bearing on soil phenomena.

[2] Some of the following general references may prove helpful:

Ramann, E., *Kolloidstudien bei Bodenkundlichen Arbeiten;* Kolloidchemische Beihefte; Band II, Heft 8/9, Seite 285-303, 1911.

Niklas, H., *Die Kolloidchemie und ihre Bedeutung für Bodenkunde, Geologie, und Mineralogie;* Internat. Mitt. für Bodenkunde, Band II, Heft 5, Seite 383-403, 1913.

Bancroft, W. D., *The Theory of Colloid Chemistry;* Jour. Phys. Chem., Vol. 18, No. 7, pp. 549-558, 1914.

Taylor, W. W., *The Chemistry of Colloids;* New York, 1915.

Burton, E. F., *The Physical Properties of Colloidal Solutions;* London, 1916.

Zsigmondy, R., *The Chemistry of Colloids,* Part I; trans. by E. B. Spear, New York, 1917.

Wiegner, G., *Boden und Bodenbildung;* Dresden and Leipzig, 1918.

Bancroft, W. D., *Applied Colloidal Chemistry;* New York, 1921.

Thatcher, R. W., *Chemistry of Plant Life;* Chap. XV, New York, 1921.

is distributed through a second, which may also be a gas, a liquid, or a solid. The material in the finely divided state is called the dispersed phase, while the matter containing it is designated as the continuous or dispersive medium. A very good example of a colloidal system occurs when very fine clay particles (solids) are suspended in water (liquid) or when an emulsion of oil and water is formed, the oil under certain conditions becoming the dispersed material, heterogeneously disposed. The particles of material in a colloidal state in these cases are so small that they will not sink as long as conditions are stable. Moreover, they exhibit the Brownian movement,[1] the oscillations increasing very rapidly as the size decreases. Such particles are molecular complexes and the solution is heterogeneous. In this respect a colloidal solution differs from a true solution, which is homogeneous, the particles being molecules and often ions.

69. Size of colloidal particles.—The size of the particles of matter in a colloidal state vary with the material and with the conditions of formation. The diameters of material in a colloidal state are considered to range from 100 μ μ[2] (.0001 m.m.) to 1 μ μ (.000001 m.m.). Above 100 μ μ suspended material is usually sinkable, while below 1 μ μ the particles generally become single molecules and a true solution is attained. Theoretically it would seem possible to pass from a suspension to a true solution without a break by a progressive subdivision of particles. There seems to be a discontinuity, however, between the colloidal state and a true solution. As the molecular complexes subdivide, they at last go into solution and may reprecipitate as coarser complexes, thus

[1] Small particles, even those well within the range of ordinary microscopic vision, exhibit, when suspended in a liquid, an oscillating motion around a central position. This movement, which is called the Brownian, is inversely proportional to the size of the particle. It is probably due to the bombardment of the molecules and ions of the liquid in which the particle is suspended. The Brownian movement is very slow for particles of a diameter of .001 mm.

[2] A micron (μ) = .001 mm. or 10^{-3} mm. A millimicron ($1\mu\mu$) = .000001 mm. or 10^{-6} mm.

maintaining a considerable gap between the two states of matter.[1]

70. The phases of a colloidal state.—As already emphasized, two phases are necessary for a colloidal state—a dispersive medium and a material that will heterogeneously disperse therein. Threee materials may function as a dispersive medium—a liquid, a solid, or a gas. In the same way, with each dispersed material there are three possibilities—a liquid, a solid, or a gas. This gives eight general phases to be considered in colloidal chemistry.[2]

The liquid-solid and the liquid-liquid phases are by far the most important as far as soil materials are concerned. The dispersed materials of soil colloids are the minerals either in a hydrous or non-hydrous condition and the organic matter in various stages of decay. The dispersive medium is of course the soil solution.

71. Colloids vs. crystalloids.—It must not be inferred, because the colloidal state is often wrongly contrasted with the crystalloidal, that material in a colloidal condition is always amorphous. It is often crystalline. Moreover, it may be animate, as some bacteria are minute enough to function colloidally. It is obvious also that the same chemical material may exist either in the colloidal or non-colloidal state. For example, silicic acid, hydrated ferric oxide, gold, carbon black,

[1] Bancroft, W. D., *Applied Colloidal Chemistry*, p. 183; New York 1921.

[2] The eight phases with examples are:

Solid in solid	Carbon in steel.
Liquid in solid	water of crystallization
Gas in solid	gases in minerals
Solid in liquid	colloidal solution of metals
Liquid in liquid	emulsions of oil in water
Gas in liquid	air in water, foam
Solid in gas	smoke in air
Liquid in gas	clouds
Gas in gas	noncolloidal, merely a mixture of molecules.

After Burton, E. F., *The Physical Properties of Colloidal Solutions*, p. 10; London, 1916.

and other materials, may or may not be colloidal, according to circumstances. The fineness of division is the explanation of colloidal properties. In order to place such a discussion on a more understandable basis, a few additional illustrations may not be amiss. The following materials, which may exist in a colloidal condition, are for convenience grouped under two general heads, organic and inorganic:

Organic: Gelatin, agar, caramel, albumin, starch jelly, humus, some bacteria, carbon black, and tannic acid.

Inorganic: Gold, silver, hydrated ferric oxide, arsenious sulphide, zinc oxide, silver iodide, Prussian blue, and the like.

72. The properties of colloidal materials.—In general, there are certain properties which materials in a colloidal state exhibit and by which they are distinguished from true solutions. In the first place, since they are not in true solution, they exert little or no effect on the freezing point and the vapor pressure of liquids. Some colloids have absolutely no effect on these properties, while others, as they allow a certain small amount of true solution to take place, do possess such influences to a slight degree. Secondly, colloids do not pass readily through semi-permeable membranes, such as parchment paper or pig's bladder. Their diffusive powers are low. This serves as an easy way of separating colloidal and non-colloidal material. Thirdly, heat and the addition of electrolytes will serve to coagulate certain colloids, a property which again serves to distinguish them sharply from a true solution. Fourthly, colloidal material has great absorptive power, not only for water, but also for gases and materials in solution, a quality of extreme importance in soil phenomena.

Many colloids are coagulated by the addition of an electrolyte,[1] the phenomenon often being spoken of as floccula-

[1] An electrolyte is any substance which has the ability when in solution to carry an electric current, the substance suffering decomposition thereby. The current is carried by the liberated ions. Hydrochloric acid, for example, dissociates into ionic hydrogen and ionic chlorine, the

tion.[1] A very good example is afforded by treating a colloidal clay suspension with a little calcium hydroxide. The tiny particles almost immediately coalesce into floccules, and because of their combined weight, sink to the bottom of the containing vessel, leaving the supernatant liquid clear. The same action will take place in the soil itself, but of course with less rapidity and under conditions less noticeable to the eye. Some dispersed materials, when thus separated from their dispersive medium, will reassume the colloidal state with ease when an opportunity is offered. In other cases, the colloidal condition is difficult to restore. Gelatin is an example of the first group and is called a reversible colloid. Ferric hydrate is an example of the more or less irreversible type.

Just why this phenomenon of flocculation or agglutination takes place is rather difficult to state. It is found that certain colloids, when subjected to the proper electric current, will migrate to either the positive (anode) or the negative (cathode) pole. These particles evidently carry a charge of electricity. Hydrated ferric oxide, aluminium hydrate, and basic dyes, for example, move toward the cathode and carry a positive charge; while arsenious sulphide, silicic acid, gold, silver, humus and acid dyes move toward the anode and are negative. It is assumed that as long as the colloidal particles remain charged, they repel each other and the colloidal state persists. When an electrolyte is added, which develops by ionization a dominant opposite charge, it is supposed to cause a neutralization of the repellent electricity carried by the colloidal particles, and flocculation occurs.

Certain colloids may flocculate certain others, as the gelatinization of silic acid by hydrated ferric oxide. At times one colloid may protect another, probably by surrounding it

former carrying a positive and the latter a negative charge of electricity ($H^+ + Cl^-$). KNO_3 gives $K^+ + NO_3^-$. The ionization varies with the substance, the dilution and certain other conditions.

[1] See Wolkoff, M. I., *Flocculation of Soil Colloidal Solutions;* Soil Sci., Vol. I, No. 6, pp. 585-601, June, 1916. A good bibliography is appended.

with a protective film. Such a case may be shown by adding gelatin to a clay suspension. When a colloid such as hydrated ferric oxide is flocculated, it loses to a certain extent its colloidal properties, and assumes the characteristics of non-colloidal materials.

73. Soil colloids and their generation.[1]—In soils there seem to exist two very general and indefinite groups of colloidal materials, besides all gradations and variations: (1) viscous, gelatinizing and reversible colloids, and (2) non-viscous, non-gelatinizing, easily coagulable and irreversible colloidal matter. The decaying organic materials in the soil and the mineral matter contribute liberally to both groups. Both of these groups, with their bewildering variations and gradations, play important parts in the physical and chemical phenomena of the normal soil.

The organic colloidal matter in a soil rich in decomposing tissue is obviously of great importance. Such material is very heterogeneous, very complex, and constantly changing. As yet very little study of the organic soil colloids has been made because of the difficulties presented by the problem. Humus colloids may be viscous or non-viscous, as the case may be, and may or may not be thrown down by calcium hydroxide. The absorptive power of these colloids for water, gases, and such materials as calcium, magnesium, and potassium is very highly developed—as much so, probably, as that of the inorganic colloids. These organic colloids are not only added as a part of the original plant tissue but are also formed during the tearing-down and splitting-off processes

[1] Van Bemmelen, J. M., *Dis Absorption;* Seite 114-115, Dresden, 1910. Also, *Die Absorptionsverbindungen und das Absorptsvermögen der Ackererde;* Landw. Ver. Stat., Band. 35, Seite 69-136, 1888; Way, J. T., *On Deposits of Soluble or Gelatinous Silica in the Lower Beds of the Chalk Formation;* Jour. Chem. Soc., Vol. 6, pp. 102-106, 1854. Warington, R., *On the Part Taken by Oxide of Iron and Alumina in the Adsorptive Action of Soils;* Jour. Chem. Soc., 2d ser., Vol. 6, pp. 1-19, 1868. Cushman, A. S., *The Colloid Theory of Plasticity;* Trans. Amer. Cer. Soc., Vol. 6, pp. 65-78, 1904. Ashley, H. E., *The Colloid Matter of Clay and its Measurements;* U. S. Geol. Survey, Bul. 388, 1909.

incident to bacterial activity, during which, compounds are thrown off in such a state of division as to assume the condition that has been designated as colloidal. Of course the chemical forces of weathering are also operative in this process of organic colloidal production.

While some inorganic soil colloids, as silicic acid and hydrated ferric oxide, are rather simple chemically, most of the mineral colloidal material is extremely complex. The soil, especially when of a clayey nature, always contains large amounts of complicated hydrated aluminum silicates of constantly varying constitution.[1] Such material, whether simple or complex, arises from ordinary weathering reactions and develops in the soil as the latter is built up. A simple example may be cited. When a feldspar undergoes decomposition the following reaction may be used to illustrate the possible change that takes place:

$$2KAlSi_3O_8 + 2H_2O + CO_2 = H_4Al_2Si_2O_9 + 4SiO_2 + K_2CO_3$$

Orthoclase — Water — Carbon Dioxide — Kaolinite — Silica — Potassium Carbonate

Kaolin almost always originates in this way, an alkali carbonate and silica being formed at the same time. The process is essentially one of hydration and carbonation; the carbon dioxide by reacting with the alkali permits the process to go on. The silica may go to one or more of three possible destinations, according to conditions,—to free quartz, to colloidal silica or to make up complex colloidal hydrated aluminum silicates. The last mentioned condition seems the most

[1] The Bureau of Soils have prepared a colloidal solution from soil by passing a well shaken mixture of soil and water through a Sharples centrifuge. The colloidal matter was separated from its dispersive medium by means of a porcelain filter. This ultra-clay seemed to be a mixture of various colloids and consisted mainly of hydrated aluminum silicates with varying amounts of ferric hydroxide, silicic acid, organic matter and possibly aluminum hydroxide.

Moore, C. J., Fry, W. H., and Middleton, H. E., *Methods for Determining the Amounts of Colloidal Material in Soils;* Jour. Ind. and Eng. Chem., Vol. 13, No. 6, pp. 527-530, June, 1921.

probable fate of the silica as the process is strongly one of hydration.

74. Influence of colloidal material [1] on soil properties.—

[1] The amount of matter in a colloidal state in soils is extremely variable, ranging from almost nothing in sand to a very large percentage in heavy plastic clays. There is no satisfactory means of finding the amount of colloidal material in soil. All of the available methods depend for their expression on the intensity of certain qualities, supposed to be developed by colloid content. This indicates that the methods are largely comparative rather than exact or strictly analytical in nature.

Ashley's method depends on the absorption of certain dyes to indicate the relative amount of material in a colloidal state. The difficulty in this method, however, lies in choosing the most effective dye and regulating its concentration. Moreover, different colloids vary so much in absorptive capacity for the same dye, that only roughly comparative results have thus far been possible.

Mitscherlich uses the absorptive capacity of the soil for water vapor as a colloidal index. In this method the air-dry soil in a thin layer is brought to absolute dryness over phosphorus pentoxide. It is then placed in a desiccator over a 10 per cent. solution of sulfuric acid and the condensation is hastened by a partial vacuum. The sulfuric acid is used in order to prevent the deposition of dew on the soil. After exposure for about twenty-four hours, the soils are found to have taken up their maximum moisture of condensation, which is called the hygroscopic water. The soil is then weighed, and the increase, figured to a percentage based on dry soil, is taken as a measure of colloidal content. The reverse process may also be followed, by exposing air-dry soil in a saturated atmosphere and afterwards drying over phosphorus pentoxide. The hygroscopicity of the soil, or its hygroscopic coefficient, is thus the basis for colloidal comparison.

Ashley, H. E., *The Colloid Matter of Clay and Its Measurement;* U. S. Geol. Survey, Bul. 388, 1909.

Rodewald, H., und Mitscherlich, A. E., *Die Bestimmung der Hygroskopizität;* Landw. Ver. Stat., Band 59, Seite 433-441, 1903. Also, Mitscherlich, E. A., und Floess, R., *Ein Beitrage zur Bestimmung der Hygroskopizität und zur Bewertung der physikolischen Bodenanalyse;* Internat. Mitt. f. Bodenkunde, Band 1, Heft 5, Seite 463-480, 1912.

Ehrenberg, P., und Pick, H., *Beitrage zur Physikalischen Bodenuntersuchung;* Zeit. f. Forst- und Jagdwesen, Band 43, Seite 35-47, 1911. Also, Vageler, P., *Die Rodewald-Mitscherlichsche Theorie der Hygroskopizität vom Standpunkte der Colloidchemie und ihr Wert zur Beurteitung der Böden;* Fuhling's Landw. Zeit., Band 61, Heft 3, Seite 73-83, 1912.

Stremme, H., and Aarnio, B., *Die Bestimmung des Gehaltes anorganischer Kolloide in Zersetzten Gesteinen und deren tonigen Unlagerungsprodukten;* Zeitsch. f. Prak. Geol., Band 19, Seite 329-349, 1911.

Tempany, H. A., *Shrinkage in Soils;* Jour. Agr. Sci., Vol. VIII, Pt. 3, pp. 312-330, June, 1917.

Beaumont, A. B., *Studies in the Reversibility of the Colloidal Condition of Soils;* Cornell Agr. Exp. Sta., Memoir 21, Apr., 1919.

As may naturally be inferred the influence of the colloidal matter on soil conditions, especially as related to plants, is extremely important. This influence is exerted in a number of ways, modifying the physical and chemical as well as the biological activities within the soil.

One important attribute imparted to soil by colloid development is high absorptive power. This power extends not only to condensation of gases, but also to water and to materials in solution. The water of condensation on dry soil particles when exposed to a saturated atmosphere is largely determined by the colloidal content. The absorptive capacity for materials in solution affects both bases and acid radicals, although the former is usually more strongly influenced. This has a very important bearing on the economic use of fertilizers and on the loss of plant nutrients from the soil. Colloidal material may also function as a catalyst[1] in that it may force certain reactions that otherwise might proceed but slowly.

Since an adjustment is always taking place between the soil colloidal material and the soil solution as far as soluble constituents are concerned, it is readily seen that not only the concentration but also the composition of the latter is at least partially a function of the colloidal matter of the soil. Colloidal matter, moreover, does not exert the same absorptive power for all material but is capable of a certain amount of selection. For example, if ammonium sulfate is added to a soil, the ammonia is strongly taken up, which tends to release the sulfate ion. The continuous use of such a fertilizer on a soil low in active bases will ultimately result in an acid condition. This is another example of the practical importance of the soil colloidal matter.

The movement of air and water in the soil is strongly influenced by colloidal materials. In a fine soil in which the individual pore spaces are normally very minute the develop-

[1] A catalyst is a material capable of hastening or retarding a chemical reaction, the catalytic agent itself not entering into the reaction.

ment of colloidal matter may seriously interfere with aëration and capillary movement of water. The loosening of a clay soil tends to ameliorate such conditions and to counteract

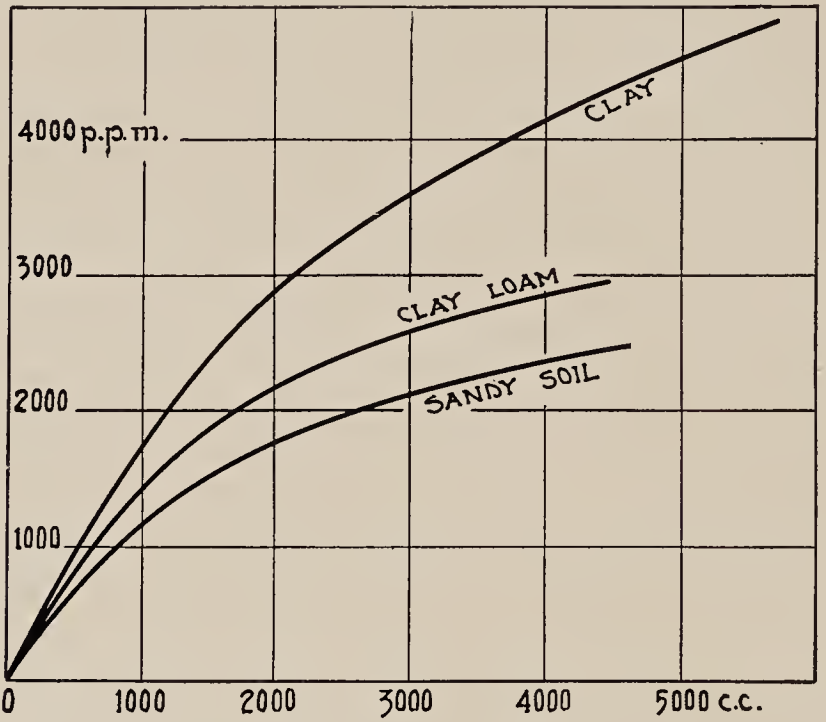


FIG. 23.—Curves showing the absorption of PO_4 in parts per million by various soils from a solution of mono-calcium phosphate containing 200 parts to the million of PO_4. The volume of the percolate is used as the abscissas. Such absorption is a rough measure of the colloidal content of a soil.

the unfavorable influence of the colloidal condition of the soil. Such a structural condition is largely ascribed to the plasticity and cohesion[1] of the soil, which are in turn, of

[1] Any material which allows a change of form without rupture and which will retain this form when the pressure is removed, is said to be plastic. Putty with a proper admixture of oil is a very good example of a plastic body. As is well known, various materials differ in plasticity.

Very closely correlated with plasticity, but not in exact similarity, is cohesion. By the cohesion of a soil is meant the tendency that its particles exhibit in sticking together and in conserving the mass intact.

course, governed by the amount and the quality of colloidal matter present.[1]

In general it is found that, other conditions being equal, an increase of certain types of colloidal matter increases plasticity; in other words, the ease with which a soil may be worked into a puddled condition becomes greater. This is a rather undesirable quality when too pronounced, and in clays, in which it is most likely to be developed because of the presence of large amounts of mineral colloids, some means of decreasing the colloidal influence is advisable. This great plasticity is developed because the colloids, especially those of a gelatinous and viscous nature, facilitate the ease with which the particles may move over one another and yet cohere sufficiently to prevent disruption of the mass. In general, also, the greater the plasticity of a soil, the greater is the cohesion when dry. In soils, then, in which certain kinds of colloidal materials are very high, clodding may occur if the soil is tilled too dry because of the great tendency of the particles to cohere. Cohesion and plasticity, as factors in soil structure, soil granulation, and tilth will receive further attention later.

It must not be inferred from the preceding discussion that the generation of colloidal matter is always detrimental to soil conditions. In sandy soils the presence of such material is extremely beneficial as it tends to bind the soil together, promotes granulation, and prevents loss of plant nutrients by leaching. It is only in heavy soils in which excessive amounts of mineral colloids may develop that a detrimental condition is likely to exist. This occurs because of a high cohesion and plasticity, because of the absorption of plant nutrients and because of tendencies toward acidity. The addition of organic

[1] Davis, N. B., *The Plasticity of Clay;* Trans. Amer. Cer. Soc., Vol. 16, pp. 65-79, 1914. Cushman, A. S., *The Colloid Theory of Plasticity;* Trans. Amer. Cer. Soc., Vol. 6, pp. 65-78, 1904. Also, Ashley, H. E., *The Colloid Matter of Clay and Its Measurement;* U. S. Geol. Survey, Bul. 388, 1909.

matter and the development of non-plastic organic colloids will do much to alleviate such conditions.

75. Resume.—The attempt to explain natural phenomena from the standpoint of crystalloidal chemistry alone is a failure. Nature has chosen to reveal herself, largely in colloidal form. Such a condition of matter is the rule and not the exception. Whether the sky, the ocean, or the land is dealt with, the larger part of the natural phenomena are plausibly explained only through knowledge of colloidal chemistry.

In general, the more complex the material and the more intricate the reactions to which it is subjected, the more likely it is that the colloidal state will result. Proteid materials, for example, whether in plants or animals, are almost always colloidal. It is to be expected, therefore, that the soil with its complicated organic and inorganic components and its rapid and complex reactions should generate colloidal matter and that material in such a state should play a prominent part in soil and plant activities.

CHAPTER VII

SOIL STRUCTURE AND ITS MODIFICATION

The structural condition of the soil is very important to plant growth, since the circulation of air and water so necessary to normal development is controlled thereby. The structural condition may be loose or compact, hard or friable, granulated or non-granulated, as the case may be. Of these conditions *granulation,* especially in heavy soils, is of vital importance, since it is really a summation of all favorable structural conditions. By granulation is meant the drawing together of the small particles around suitable nucleii, so that a crumb structure is produced. The grains thus cease to function singly. The importance of such a structural condition on a heavy soil is obvious. The soil becomes loose because of the larger units, air moves more freely, and water not only drains away readily when in excess, but responds with celerity to the osmotic pull of the plant.

76. Soil structure types.—The structural condition of a soil can generally be attributed directly to its textural nature as can readily be seen by comparing sandy and clayey soils. For convenience of discussion two general structural groups may be established: (1) single-grained, and (2) compound-grained. In the former the particles function more or less separately and the soil is, as a consequence, rather open and friable. In the latter group the particles, being small, tend to stick together and the units instead of being solid are aggregates, their size and character as well as their relations to each other being a determining factor in the physical condition of the soil. As most soils are mixtures of large, medium, and

small particles, it is only the coarse sandy soils on the one hand and very fine clayey soils on the other that ideally represent these two groups. Most soils, especially loams, present combinations of the single and compound grain structures.

Single-grain structure as found in sandy soils has certain obvious advantages, such as looseness, friability, good aëration, and drainage and easy tillage. On the other hand, such soils are often too loose and open and lack the capacity to absorb and hold sufficient moisture and nutrient materials. They are, as a consequence, likely to be droughty and lacking in fertility. There is only one method of improving in a practical field way[1] the structure of such a soil—the addition of organic matter. Organic material, if it undergoes favorable decomposition when incorporated with the soil, will not only act as a binding material for the particles but will also increase the water capacity. Nitrogen also is added and if the organic matter is properly supplemented with fertilizers and lime, the soil fertility will usually be markedly improved. A sandy soil high in organic matter is almost ideal from a structural standpoint.

The modification of the structural condition of a heavy soil is not such a simple problem as in the case of a sandy one. In the latter the plasticity and cohesion is never high even after the addition of large amounts of organic materials that rapidly develop into a colloidal state. In clays and similar soils the potential plasticity and cohesion [2] are always high

[1] In the greenhouse or garden, structure may be modified by mixing different soils. This is not practicable in the field.

[2] There are no satisfactory methods of determining either the plasticity or the cohesion of soils. For plasticity determination, see: Atterberg, A., *Dis Plastizität der Ton;* Internat. Mitt. f. Bodenkunde, Band I, Heft 1, Seite 10-43, 1911. Kinnison, C. S., *A Study of the Atterberg Plasticity Method;* Trans. Amer. Cer. Soc., Vol. 16, pp. 472-484, 1914.

For methods of estimating cohesion:

A good description of Schübler's apparatus is found on page 104 of *Bodenkunde,* by E. A. Mitscherlich, published by Paul Parey, Berlin, in 1905. Haberlandt, H., *Über die Kohäreszenz, Verhaltnisse verschiedener Bodenarten;* Forsch. a. d. Gebeite d. Agri.-Physik., Band I, Seite 148-157, 1878. Also, *Wissenschaftlich praktische Untersuchungen*

due to the presence of large amounts of complex hydrated aluminum silicates in a colloidal condition. The more plastic a soil becomes, the more likely it is to puddle,[1] especially if worked when wet. Moreover, a soil of high plasticity is prone to become hard and cloddy when dry, due to the cohesive tendencies of the small particles. Heavy soils must, therefore, be treated very carefully, especially in tillage operations. If plowed too wet, puddling occurs, the aggregation of particles is broken down, and an unfavorable structure is sure to result. If plowed too dry, great lumps are turned up which are difficult to work down into a good seed-bed. In a sandy soil, no such difficulties are encountered.[2]

Granulation or the production of a compound-grain structure is the only means of correcting the physical condition of a heavy fine-grained soil. In this process the small particles are drawn towards innumerable suitable nucleii and a porous structure is developed. The size of the individual pore spaces is thereby increased and air and water drainage is facilitated. The structural condition in reality simulates a single-grain state with this important difference, however: the particles are porous and not solid. Unless a heavy soil possesses at least some granulation, it is more or less unfit for agricultural operations. (See Fig. 24.)

77. Granulation.—While it is possible to list the factors

auf dem Gebeite des Pflanzenbaues; Band I, Seite 22, 1875. Puchner, H., *Untersuchungen über die Kohäreszenz der Bodenarten;* Forsch. a. d. Gebiete d. Agri.-Physik., Band 12, Seite 195-241, 1889. Atterberg, A., *Die Konsistenz und die Bindigkeit der Boden;* Internat. Mitt. f. Bodenkunde, Band II, Heft 2-3, Seite 149-189, 1912. Cameron, F. K., and Gallagher, F. E., *Moisture Content and Physical Condition of Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 50, 1908.

[1] When a soil in a plastic condition has been kneaded until its pore space is much reduced and it has become practically impervious to air and water, it is said to be puddled. The development of gelatinous and viscous colloidal materials seems to be the controlling factor in such a condition, the pore space of a puddled soil being largely filled with such material. When a soil in this condition dries, it becomes hard and dense.

[2] Sandy soils are often plowed rather wet in order to render them more compact than they normally would be.

that bring about granulation in a soil, it is difficult to state specifically just why this phenomenon takes place. It has been suggested that much of the granule formation in the soil is due to the contraction of the moisture around the particles when, for any reason, the moisture content is reduced. It is known that the soil particles tend to be drawn together by this reduction in the soil-moisture, due to the pulling power of the thinned films.

If to this condition is added a material which tends to exert not only a drawing power on loss of moisture, but also a bind-

FIG. 24.—A well granulated soil and a puddled soil. Organic matter plays an important rôle in structural condition.

ing and cementing power when dry, all the essentials for successful granulation are present. This second force is found in the colloidal material existing in considerable quantities in heavy soils. Such materials have already been shown to determine the cohesion of the soil. The influence of the colloidal material is considered by many authorities as the more important in the structural adjustments of the soil.

It is evident that if cohesion and plasticity are to function in granulation—or, in other words, locally in the soil instead of generally and uniformly as when clodding or puddling occurs—a certain moisture content must be maintained. In a soil subject to such a condition, the cohesive forces being

localized, the internal strains and pressures are unequal and a tendency arises for the mass to divide along lines of weakness into groups of particles. The binding capacity of colloidal material, as well as of salts deposited from the soil solution, tends to make such a crumb structure more or less permanent. The moisture content most favorable for granulation seems to be that which is optimum for plant growth.[1]

78.—Forces facilitating granulation.[2] — Granulation is nothing more or less than a favorable condition brought about by the force exerted by a variable water film and the pulling and binding capacities of colloidal material, operating at numberless localized foci. It is evident that any influence or change in the soil which will cause a greater localization of these operative forces will promote the aggregation of the particles. The addition of materials from extraneous sources is also a practice that may tend to develop lines of weakness and thus cause a more intense activity of the forces at work.

The conditions, additions, and practices tending to develop or facilitate a granular structure in soils may be listed under six heads: (1) wetting and drying of the soil, (2) freezing and thrawing, (3) addition of organic matter, (4) action of roots and animals, (5) addition of lime and (6) tillage. Only the last two need additional consideration.

79. Granulating influence of lime.[3]—One of the effects of lime in the soil, especially of the oxide and hydroxide forms,

[1] Cameron, F. K., and Gallagher, F. E., *Moisture Content and Physical Condition of Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 50, p. 8, 1908.

[2] Fippin, E. O., *Some Causes of Soil Granulation;* Trans. Amer. Soc. Agron., Vol. 2, pp. 106-121, 1910. Czermak, W., *Ein Beitrag zur Erkentuis der Veränderungen der Sog physikalischen Bodeneigenshaften durch Frost, Hitze, und die Beigabe einiger Salze;* Landw. Ver. Stat., Band 76, Heft 1-2, Seite 73-116, 1912. Also, Ehrenberg, P., und Romberg, G. F. von, *Zur Frostwirkung auf den Erdboden;* Jour. f. Landw. Band 61, Heft 1, Seite 73-86, 1913.

[3] Lime in a strictly chemical sense refers only to calcium oxide (CaO). The term is used here with an agricultural meaning, including all calcium and magnesium compounds which are ordinarily added to the soil to correct acidity, thus including not only calcium oxide but calcium hydroxide and calcium carbonate [$Ca(OH)_2$ and $CaCO_3$] as well.

is a flocculating action. This agglomeration, as already explained, is the drawing together of the finer particles of a soil mass into granules. When calcium hydroxide is mixed with water containing fine particles in suspension there is almost immediately a change in the arrangement of the particles. They first draw together in light, fluffy groups, or floccules, which then rapidly settle so that the supernatant liquid is left clear or nearly so. This phenomenon is termed flocculation, because of the peculiar appearance of the aggregates. This flocculating tendency when lime is added goes on in the soil as well as with suspensions, although more slowly. In general, the lime tends to satisfy the absorptive capacity of the colloidal material and by throwing down these colloids develops lines of weakness. The cohesive power of the soil is thus localized and agglomeration must necessarily occur. The various forms of lime differ in their flocculating capacities, calcium oxide and hydroxide being very active, while calcium carbonate is relatively inactive in this regard.

It must not be inferred that lime is generally added for its flocculating influence. It is used primarily for other reasons, the amounts applied being in general too small to have very much influence on the structural condition of the soil. Warington,[1] however, reports a statement of an English farmer to the effect that by the use of large quantities of lime on heavy clay soil, he was enabled to plow with two horses instead of three. It is generally true that soils rich in lime are well granulated, and maintain a much better physical condition than soils of the same texture that are low in lime.

80. Tillage.[2]—Tillage aims to accomplish three primary

[1] Warington, R., *Physical Properties of Soils*, p. 33, Oxford, 1900.

[2] For a very complete review of the theory and practice of plowing and cultivation, with a complete bibliography: Sewell, M. C., *Tillage: A Review of the Literature;* Jour. Amer. Soc. Agron., Vol. II, No. 7, pp. 269-290, Oct., 1919.

The following books upon the mechanics of tillage may prove helpful: Davidson, J. B., and Chase, L. W., *Farm Machinery and Farm Motors;* New York, 1908.

The Oliver Plow Book; South Bend, Ind., 1920.

purposes: (1) modification of the structure of the soil; (2) disposal of rubbish or other coarse material on the surface, and the incorporation of manures and fertilizers into the soil; and (3) the deposition of seeds and plants in the soil in position for growth.

The most prominent of these purposes is the modification of the soil structure. This affects the retention and movement of moisture and air, the absorption and retention of heat, and either promotes or retards the growth of organisms. The creation of a soil-mulch is merely a change in the structure of the soil at such times and in such a manner as may prevent the evaporation of moisture. In fine-textured soils, in which

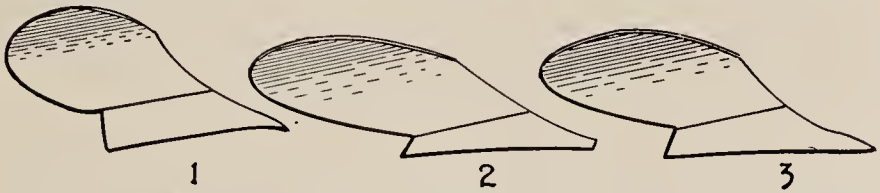


FIG. 25.—Three types of plow bottoms; 1, stubble; 2, sod; 3, general purpose.

the granular structure is most desired, tillage may have an important influence on the formation or destruction of granules. As has been pointed out, any treatment that increases the number of lines of weakness in the soil structure facilitates the activities of the moisture films and the colloidal materials in producing soil granules. Tillage shatters the soil and breaks it into many small aggregates, which may be drawn together and loosely cemented as a result of the evaporation of moisture. The more numerous the lines of weakness produced, the more pronounced is the granulation; and, conversely, the fewer the lines of weakness produced, the more coarse and cloddy is the structure.

According to their mode of action, tillage implements may

Ramsower, H. C., *Equipment for the Farm and Farmstead;* Boston, 1917.

King, F. H., *Physics of Agriculture;* Chap. XI, Madison, Wis., 1910.

be grouped as follows: plows, cultivators, packers and crushers.

81. The action of the plow.—The moldboard plow brings about its effects because of the differential stresses set up in the furrow slice as it passes over the share and the moldboard. The soil in immediate contact with the plow surface is retarded by friction, and the layers above tend to slide over one another much as the leaves of a book when they are bent. If the soil is in just the proper condition, maximum granulation results; but if the moisture is too high or too low, puddling or clodding may follow, especially on a heavy soil.

Not only does a shearing occur, but this shearing is differential, due to the slope of the share and especially to the curve of the moldboard. When the soil is to be turned over with the least expenditure of energy, the share is sloping and is set to deliver a slanting cut, and the moldboard is long and gently inclined. This allows the furrow slice to be turned with little granulation and with a minimum effort. When maximum granulation and pulverization are desired, the moldboard is short and sharply turned, and the share is less sloping and the cutting edge less slanting. Such conditions make for the development of more friction and the generation of those internal twisting and shearing stresses necessary for good granulation. The sharper the bending of the furrow slice, the greater are the internal stresses set up. Various types of moldboards and shares designated for special soils and particular operations are on the market. (See Fig. 25.)

The disc plow is a sharp rolling disc set at such an angle that it slices off and turns over the soil, pulverizing it fairly effectively somewhat after the manner of the moldboard plow. One advantage of the disc plow is its lighter draft, due to a rolling rather than a sliding friction in the soil. In practice it is especially effective on very dry, hard soil.

While the plow is the very best pulverizing agent when optimum soil-moisture conditions prevail, it is also a most

effective puddling agent when the soil is wet. Therefore, care in the judging of optimum conditions for plowing is a most important feature in the maintenance and encouragement of soil granulation. A careful study of the moisture conditions in a clay soil is especially necessary in order to determine just what is the correct moisture content for good plowing. That this condition must be gauged carefully and immediate use made of the advantages it offers is shown by its narrow limits. A few days may suffice for the moisture to pass through and beyond such a condition. A clay soil is so

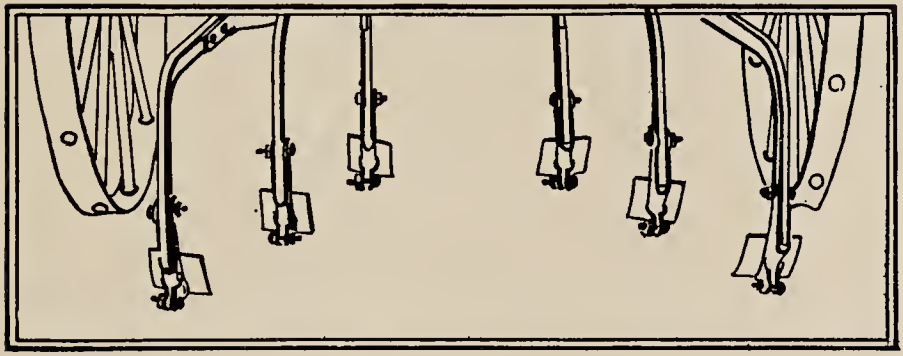


FIG. 26.—A six-shovel cultivator.

difficult to handle at best that no opportunities such as are offered by optimum moisture conditions should be lost. Moreover, a heavy soil plowed too dry or too wet does not regain its normal granular condition for several seasons. Such care is unnecessary with a sandy soil.

82. Cultivators, packers and crushers.—The many types of cultivators may be grouped under three heads: (1) cultivators proper, (2) levelers and harrows, and (3) seeder cultivators. The action of all these implements is the same in that they stir the soil, at the same time loosening the structure and cutting off weeds. While the action is much shallower than with the plow, the same attention should be paid to moisture conditions. Particularly is this true in pulveriza-

tion immediately after plowing. When the moisture conditions are optimum, the clods are more easily shattered and the formation of a suitable seed-bed is speedily accomplished.

The cultivators proper are well represented by the ordinary corn cultivator whether equipped with shovels, knives or discs. Under the leveler and harrow type may be placed the spike and spring-tooth harrow, the various kinds of weeders, the acme harrow and the disc harrow. The latter may be equipped with solid, cut-away, or spading discs. The grain drill, either of the press or disc type, is a representative of the seeder cultivators, which considerably influence the structural condition of the soil although such action is not their primary purpose. (See Fig. 26.)

Packing and crushing are ordinarily performed by the same implement, since any tool that compacts does a certain amount of crushing; and, conversely, any implement that crushes the soil does some compacting. Such an implement as the cultipacker cultivates, packs and promotes granulation in one operation. The difficulty of establishing a rigid classification is evident.

Rollers may be of the solid or barrel type, the corrugated type, or the bar type. The subsurface packer is also included in this group. Rollers tend to force the soil particles nearer together and smooth the surface. If at the same time they establish a soil-mulch so much the better. The rolling of the land after seeding is an attempt to stimulate the capillary movement of the water and to hasten germination by bringing the seed in closer contact with the soil.

The planker, drag, or float is a common type of single crusher. It is generally broad and heavy, without teeth and is dragged over the soil. The lumps are rolled under its edges and ground together in such a manner as effectively to reduce their size. The soil is leveled and smoothed at the same time. This implement may be used instead of a roller in many cases. (See Fig. 27.)

83. Soil tilth.—The previous data and discussion have clearly shown the very great importance of structure in the successful handling of the soil in the field. Since good physical condition will reflect itself on crop yield it is evident that structure must ultimately be considered in relation to all plant growth. This relationship is usually expressed by the term *tilth*. While structure refers to the arrangement of the particles in general, and granulation to a particular aggregate condition, tilth goes one step farther and includes the plant. Tilth, then, refers to the physical condition of the soil

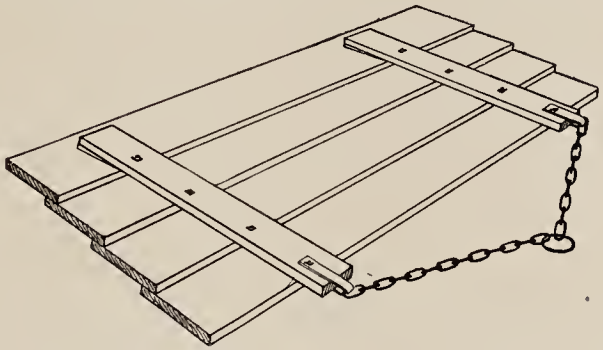


FIG. 27.—A planker or drag, useful in the crushing of clods.

as related to crop growth. It may be poor, medium, good, or excellent, according to circumstances. Good tilth may demand in many soils maximum granulation, in others only a medium development. Tillage operations by influencing the structure of the soil aim to develop optimum tilth. Optimum tilth always implies the presence of water since the best physical relationships cannot be developed without such moisture conditions.

84. Summary.—The factors which control the structural condition of the soil to the greatest extent are plasticity and cohesion, their influence intensity being due directly to the presence of certain kinds of materials, especially hydrated aluminum silicates, in a colloidal state. As plasticity and cohesion increase the tendencies of a soil to puddle when wet

and to clod when dry are augmented. Therefore in heavy soils a modification in these factors is advisable, through a careful control of moisture and a bettering of the granular structure of the soil. Granulation, while due to some extent to the influence of the water film, is traceable largely to colloidal matter both mineral and organic. It is really a concentration of the forces of cohesion and plasticity around numberless localized foci. Granulation takes place under the influence of wetting and drying, freezing, plants and animals, addition of lime and organic matter, and tillage operations, especially plowing. The farmer exerts a modifying influence on structure most efficiently by increasing the organic content of the soil and by plowing. He is, of course, aided and abetted by natural forces.

Efficient tillage requires good judgment in the selection of proper implements and mechanical skill in their operation. It demands besides an understanding of the properties of soils and a knowledge of their plant relationships. Sandy soils are easily handled provided sufficient organic matter is maintained. Such cannot be said of clayey soils. Due to the high cohesion and plasticity of heavy soils the moisture zone for successful tillage is particularly narrow. The ability to detect when this zone has been reached in a clay soil is one of the essentials of its successful management. Another essential is the effective widening of such a zone by granulation operations.

The optimum moisture condition for tillage is generally near the optimum condition for plant growth—a happy coincidence, since by regulating the moisture content for plant development conditions are rendered most favorable for all soil activities. It is thus possible to produce in one operation that desideratum in all soil physical operations, an optimum tilth.

CHAPTER VIII

THE FORMS OF SOIL-WATER AND THEIR CHARACTERISTICS [1]

A SOIL, in order to function as a medium for plant growth, must contain a certain amount of water. This moisture promotes the innumerable chemical and biological activities of the soil, it acts as a solvent and carrier of nutrients, and in addition it functions as a nutrient itself. The amount, character, and control of the soil-moisture must evidently be reckoned with in any study of soil and plant relationships, whether they are of a practical or a theoretical nature. The productivity of a soil is often a direct function of its moisture condition.

85. Forms of soil-water.—As has already been demonstrated, a soil of a given volume weight has a definite pore space which may be occupied largely by air or by water, or shared by both, as the case may be. Of course, an ideal soil for growth is one in which there is both air and water, the proportions depending on the texture and the structure of the soil and the character of the crop. Assuming for the time being, however, that the pore space is almost entirely filled with water, or, in other words, that the soil is saturated, three forms of water are found to be present—*hygroscopic, capillary* and *gravitational.* These forms differ not only in the amount and proportion of the solutes which they carry but also in the positions that they occupy in their relation to the larger soil particles and the accompanying colloidal complexes.

[1] Keen, B. A., *Relations Existing Between the Soil and Its Water Content;* Jour. Agr. Sci., Vol. X, Part 1, pp. 44-71, Jan., 1920. A good review of the subject.

If an absolutely dry soil is exposed to a moist atmosphere, it will absorb moisture rather rapidly until the colloidal surfaces are in equilibrium with the air as far as water vapor is concerned. Other conditions being equal, maximum water will be taken up from an atmosphere which is saturated with moisture. The moisture thus taken up is called hygroscopic water, its amount being determined quite largely by the magnitude of the colloidal material present in the soil.

On adding more water, it will be found that the absorptive power of the soil has been by no means satisfied by the hygroscopic water. Moisture will still be taken up by the colloidal complexes and it will also collect in the interstices between the soil particles. This water which is above and beyond the hygroscopic is generally called the capillary. That part held by the colloidal complexes is very similar in characteristics to the hygroscopic water in that it is tightly held and is more or less immovable. That portion in the interstices, especially the larger spaces, is in the form of a film, is loosely held, and responds to capillary action. While typical capillary water is much different from hygroscopic moisture, it grades into the latter with no sharp line of demarcation.

Once the capillary capacity of the soil is satisfied, a third form of water may appear. This water is but slightly influenced either by the colloidal complexes or the larger soil particles and consequently is free to respond to the pull of gravity. It is called the free or gravitational moisture and is the water which passes through the soil and appears in streams and rivers bearing in solution the tremendous amounts of soluble salts which are every year lost from the land.

86. Hygroscopic water.—The hygroscopic water in a soil has been spoken of as the water of condensation, or absorption. It is, however, quite distinct from water condensed on a surface colder than the moist atmosphere in which it is placed. All bodies possess the power, to a greater or less degree, of absorbing water even when at the same temperature

as the air with which they are in contact, provided, of course, that the air contains water-vapor. Such condensation is largely a function of the surface exposed.

One of the characteristics peculiar to colloidal materials is a high absorptive power for water, whether it is presented in the form of a liquid or vapor. This capacity is due to the tremendous surface exposed by matter in a colloidal state, which not only may hold the moisture physically but may even force it into loose chemical combination.[1] The hygroscopic water is probably not in the form of a film around the particles but in a much more intimate relationship. That which is held physically is probably, in part at least, in a condition of solid solution. If any of the hygroscopic water is held chemically, the bond is probably a rather loose one.

A large proportion of the hygroscopic moisture is obviously not in a liquid state and consequently is immovable as such. When a hygroscopically saturated soil is exposed to a partially saturated air, a portion of the hygroscopic moisture will be lost through vaporization. In order to expel the remainder of the hygroscopic water, the soil must be heated. For convenience of determination, it is generally assumed that all of the hygroscopic moisture will be driven from an air-dry soil by heating it for four or five hours at a temperature of 100° or 110° C. This is only an assumption, however, as some of the moisture in intimate relationship with the colloidal complexes probably still remains.

The amount of energy necessary to expel the hygroscopic moisture from the soil is very great, since its only movement is thermal and because it is held so closely. As so much energy is expended in removing this water, it is reasonable to

[1] See, Bouyoucos, G. J., *Classification and Measurement of the Different Forms of Water in the Soil by Means of the Dilatometer Method;* Mich. Agr. Exp. Sta., Tech. Bul. 36, Sept., 1917. *Relationship between the Unfree Water and the Heat of Wetting of Soils and its Significance;* Mich. Agr. Exp. Sta., Tech. Bul. 42, Mar., 1918. *A New Classification of the Soil Moisture;* Soil Sci., Vol. XI, No. 1, pp. 33-47, Jan., 1921.

expect that a certain amount of heat of condensation will be apparent when it is resumed.[1] Patten [2] and Bouyoucos [3] offer the following quantitative data concerning this point:

TABLE XXVIII

HEAT EVOLVED BY WETTING SOILS DRIED AT 110° C.

Soil	Calories to a Kilo of Dry Soil
Quartz sand	000
Norfolk sand	347
Hagerstown loam	1108
Miami silt loam	1742
Cecil clay	3376
Superior clay	5158
Muck (25% organic matter)	6413
Peat	22185

87. Determination of the hygroscopic coefficient.— The methods for the determination of the maximum hygroscopicity of a soil, or, in other words, the *hygroscopic coefficient,* are simple in outline. The soil, in a thin layer, is exposed to an atmosphere of definite humidity under conditions of constant temperature and pressure. Complications arise from the necessity of using a very thin layer of soil, from the difficulty of controlling humidity, and from the tendency of capillary water to form in the soil interstices before the hygroscopic capacity is satisfied. The question of how long the exposure should take place has not been definitely settled. It

[1] The tremendous heat of wetting is probably due to the latent heat of water, to the attraction that soils have for water and to the condition into which the water is transformed. The heat of condensation is so large as to suggest the probability of a change in the aggregation of the moisture thus absorbed.

[2] Patten, H. E., *Heat Transference in Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 59, p. 34, 1909.

[3] Bouyoucos, G. J., *Relationship between the Unfree Water and the Heat of Wetting of Soils and its Significance;* Mich. Agr. Exp. Sta., Tech. Bul. 42, Mar. 1918.

is evident, therefore, that not only must any method be more or less arbitrary but that its value can only be comparative.

In the actual procedure,[1] the sample of soil may be air-dried or dried at 100° or 110° C. If the former method is followed, the sample after exposure is heated for four or five hours at 100° or 110° C., the loss being considered as hygroscopic water. If oven-dried soil is utilized, the gain in weight due to the exposure to the moist air is the hygroscopic moisture. If a saturated air is made use of, the gain is maximum hygroscopicity, from which can be calculated the percentage of hygroscopic water based on dry soil, called the hygroscopic coefficient. If a partially saturated air is utilized, a sample of stock soil, the hygroscopic coefficient of which is known, is exposed at the same time. The determination on the known sample shows what proportion of possible hygroscopic water has been taken up. From this the hygroscopic coefficient of the unknown soil sample can be calculated.[2]

88. Hygroscopic capacity of soils.—Since hygroscopicity depends almost directly on the colloidal nature of the soil, it is evident that texture, external factors being under control, will be an important factor in determining the hygroscopic coefficient. When the organic matter of soils is more or less the same in amount, the inorganic colloids seem to con-

[1] Hilgard, E. W., *Soils;* pp. 196-201, New York, 1911. This method is practically the same as that used for the comparative estimation of the colloidal content of the soil, the hygroscopic coefficient being the comparative figure obtained. See note to paragraph 74 of this text.

Bouyoucos determines the hygroscopic coefficient in an approximate way by means of the dilatometer method. The dilatometer is an apparatus which measures the expansion of water on freezing. If a given amount of soil and water is reduced below zero, the expansion attained will reveal the amount of water remaining unfrozen, due to its soil relationships. Bouyoucos finds that the amount of moisture unfrozen after supercooling to –4° C. (slightly more freezes at –78° C.) correlates fairly well with the hygroscopic coefficient. Bouyoucos, G. J., *A New Classification of Soil Moisture;* Soil Sci., Vol. XI, No. 1, pp. 33-47, Jan., 1921.

[2] Alway, F. J., and Clarke, V. L., *Use of Two Indirect Methods for the Determination of the Hygroscopic Coefficients of Soils;* Jour. Agr. Res., Vol. VII, No. 8, pp. 345-351, Nov., 1916.

trol the hygroscopicity. The following figures from Briggs and Schantz,[1] by whom the hygroscopic coefficient was determined by exposing air-dry soil at 20° C. to a saturated atmosphere and then drying at 110° C., illustrate this point. The organic matter was not a serious disturbing factor.

TABLE XXIX

HYGROSCOPIC CAPACITY OF VARIOUS SOILS EXPRESSED IN PERCENTAGE BASED ON DRY SOIL[2]

SOILS	PERCENTAGE OF CLAY	HYGROSCOPIC COEFFICIENT
Coarse sand	1.6	.5
Fine sand	3.9	1.5
Sandy loam	7.5	3.5
Fine sandy loam	12.9	6.6
Loam	14.4	9.6
Clay loam	22.0	11.4
Clay	32.5	13.2

[1] Briggs, L. J., and Schantz, H. L., *The Wilting Coefficient for Different Plants and Its Indirect Determination;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 230, p. 65, Feb., 1912. See also, Loughridge, R. H., *Investigations in Soils Physics;* Calif. Agr. Exp. Sta., Rep. of Work of the Agr. Exp. Stations of Calif. for 1892-3-4, pp. 76-77. Ammon, Georg., *Untersuchungen über das Condensationsvermögen der Bodenconstituenten fur Gase;* Forsch. a. d. Gebiete d. Agri.-Physik., Band II, Seite 1-46, 1879. Dobeneck, A. F., von, *Untersuchungen über das Absorptionsvermögen und die Hygroskopizität der Bodenkonstituenten;* Forsch. a. d. Gebiete d. Agri.-Physik., Band XV, Seite 163-228, 1892.

[2] During the many years of soil investigation, especially where the problems had to deal either directly or indirectly with moisture, five methods of water expression have been evolved, their use depending on the nature of the work and on the points to be expressed. They may be listed under two general heads:

A. Percentage expression
   1. Percentage on a dry basis
   2. Percentage on a wet basis

B. Volume expression
   1. Cubic inches to the cubic foot of soil
   2. Percentage by volume
   3. Surface inches

A soil carrying 25 per cent. of water on the dry soil basis contains 20 per cent. on the moist basis (soil plus water). The former method is

Apparently, the finer the soil, the higher the hygroscopic coefficient. This is due to the fact that most of the inorganic colloidal matter is carried by the finer separates. In considering the hygroscopicity, however, the influence of the organic matter must not be forgotten. Organic colloidal matter has a very marked influence on absorption, and as the organic matter of the soil increases, the hygroscopicity rises rapidly. The following data from Beaumont[1] is interesting in this respect:

TABLE XXX

THE HYGROSCOPIC COEFFICIENT[2] COMPARED TO CERTAIN OTHER SOIL FACTORS

Soil	Clay %	Ignition %	Humus %	Hygroscopic Coefficient %
Dunkirk silty clay loam, surface	12.9	5.08	1.26	3.80
Dunkirk silty clay loam, subsoil	20.0	3.05	.20	5.77
Clyde clay loam, surface.....	20.1	14.54	4.34	18.90
Vergennes clay, subsoil.....	74.5	5.79	.49	17.40

In comparing the two Dunkirk soils it is apparent that the colloidal clay is the dominant factor in determining the mag-

preferable in that the basis for calculation is not a changeable one as is the weight of moist soil. The dry basis is practically always used in soil work.

Where two soils of different volume weight are compared, the percentage relationship does not give a true idea of the relative amounts of water present. A volume expression should then be used. If a cubic foot of soil, weighing 100 pounds, contains 10 pounds of water it would be carrying (10×27.6) or 276 cubic inches of water. This would equal $(276 \div 1728) \times 100$ or 15.9 per cent. by volume or $(10 \div 5.2) = 1.92$ surface inches.

[1] Beaumont, A. B., *Studies in the Reversibility of the Colloidal Condition of Soils;* Cornell Agr. Exp. Sta., Memoir 21, pp. 501-504, April, 1919.

[2] Moisture content in this text unless otherwise indicated will always be expressed on the dry soil basis.

nitude of the hygroscopic coefficient. With the Clyde and Vergennes, however, the organic colloidal matter is dominant, since the Clyde with only 20 per cent. of clay has a higher hygroscopic figure than the Vergennes which carries 74.5 per cent. of that separate. The Clyde clay loam and the Dunkirk subsoil have the same amount of clay, yet the former possesses a hygroscopic coefficient over three times larger.

Two external conditions seem to be important in determining the amount of hygroscopic water in soils—(1) humidity and (2) temperature. It has been definitely established that the higher the humidity the higher the content of hygroscopic moisture. An air-dry soil will, therefore, contain less moisture in a dry atmosphere than in one carrying large amounts of water-vapor. When the soil is in contact with a saturated air it will take up hygroscopic water to its full capacity and be at the point spoken of as the hygroscopic coefficient. As the soil air is generally considered to be saturated or almost saturated with water-vapor,[1] except in the surface layers or during periods of protracted drought, a soil in normal condition may be considered, for all practical purposes, to be at its maximum hygroscopicity. An increase of the temperature of the saturated atmosphere seems to increase hygroscopicity. With a partially saturated air the influence seems to be in the opposite direction.[2] This, however, is not an important practical point.

The hygroscopic coefficient, defined as the maximum hygroscopic water that a soil will hold, is controlled largely by the texture and organic content of the soil. It may vary from a very low figure in a sandy soil to as high as 15 per cent. for a clay high in organic matter. With a muck or peat, the per-

[1] Russell, E. J., and Applyard, A., *The Atmosphere of the Soil: Its Composition and Causes of Variation;* Jour. Agr. Sci., Vol. VII, Part 1, p. 5, 1915.

[2] For a full discussion of this point, see Lipman, C. B., and Sharp, L. T., *A Contribution to the Subject of the Hygroscopic Moisture of Soils;* Jour. Phys. Chem., Vol. 15, No. 8, pp. 709-722, Nov., 1911.

centage would be considerably higher, in some cases reaching 50 or 60 per cent. It must always be kept in mind, however, that the point designated as the hygroscopic coefficient is more or less arbitrary and that there is no sharp line of demarcation between the moisture designated as hygroscopic and that which lies near it, but is called capillary.

89. The capillary water.[1]—The moisture above the hygroscopic coefficient but not free to respond to gravity is generally spoken of as the capillary water. The portion of this moisture lying in contact or in the immediate neighborhood of the hygroscopic water is probably capable of only sluggish diffusion movement if any.[2] This part of the capillary moisture is held largely by the colloidal matter and may be considered as transitional between the true hygroscopic and the more active capillary portion. Although so closely related to the hygroscopic water in general properties and characteristics, the soil does not assume it by absorption from vapor-laden air. This separates it at least analytically from the hygroscopic form of moisture. Moreover, it is probably largely in the liquid state, which is hardly true of all of the hygroscopic water.

The more active capillary water exists in the large interstices and as a film over the particles and the colloidal complexes. It is held rather loosely by the soil, yet strongly enough to counteract gravitation. This part of the capillary moisture, being more or less beyond colloidal influence, is free to respond to the forces active in true solutions and, therefore, may move from place to place as equilibrium stresses may demand. While the inner portion of the capillary water is held by the absorptive power of the colloidal surfaces, the outer and freer portion is maintained by the surface tension

[1] The colloidal conceptions regarding soil-moisture has made it advisable to give the term capillary a broader significance than its root meaning justifies.

[2] Bouyoucos, G. J., *A New Classification of the Soil Moisture;* Soil Sci., Vol. XI, No. 1, pp. 33-47, Jan., 1921.

of the water film. The distinctive characteristics of these two portions of the capillary water are due to their controls—colloidal in one case, surface tensional in the other.[1]

While the outer portion of the capillary water is undoubtedly in the form of a more or less continuous film from particle to particle, the bulk of such moisture probably exists normally in the interstices between the soil grains. Such a condition arises because of the pressure developed by the force of surface tension. The pressure due to surface tension, however it may be expressed, varies with the curvature of the film and is proportional to twice the surface tension divided by the radius. The less the radius the greater the curvature and, therefore, the greater the stress developed by surface tension.[2]

The situation so far as the soil is concerned may be explained in an empirical way as follows: Suppose that two particles, each carrying a capillary water film, be brought into such contact that the films coalesce. There are now two distinct surfaces, that at A, A′ (see Fig. 28), with the curva-

[1] Bouyoucos classifies these two types of capillary water as free (the more active) and capillary-absorbed (the inner group). The distinction is made on the basis of his dilatometer results, the portion which freezes at about O°C being considered as the more active or free.

Bouyoucos, G. J., *A New Classification of the Soil Moisture;* Soil Sci., Vol. XI, No. 1, pp. 33-47, Jan., 1921.

[2] Surface tension is the tension of a liquid surface by virtue of which it acts like an elastic enveloping membrane, tending always to contract to the minimum area. While molecules in the interior portion of the liquid are attracted in all directions and are thus at equilibrium, those on the surface are attracted by an overbalancing force toward the interior. In measurement, surface tension is considered as the force with which the surface on one side of a line, one centimeter long, pulls against that on the other side of the line. It is generally expressed in dynes. The pressure due to surface tension varies with the curvature of the film. It is usually expressed as:

$$P = \frac{2T}{r}$$

where P is the pressure; T, surface tension; and r, the radius of the drop. As the radius becomes less, the curvature increases and the pressure due to surface tension increases. An increase of T will increase the pressure, P.

ture of the original film, and that at B, which is very acute and which naturally must exert a very great outward pull. Under the stress of this pull developed by the surface tension acting in this film of very great curvature, the water is drawn into the space between the particles, where it becomes thicker than the capillary film about the particles. The readjustment continues until the forces developed by the two films become equal. An equilibrium is now established. In the soil the tendency towards adjustment is somewhat similar in so far

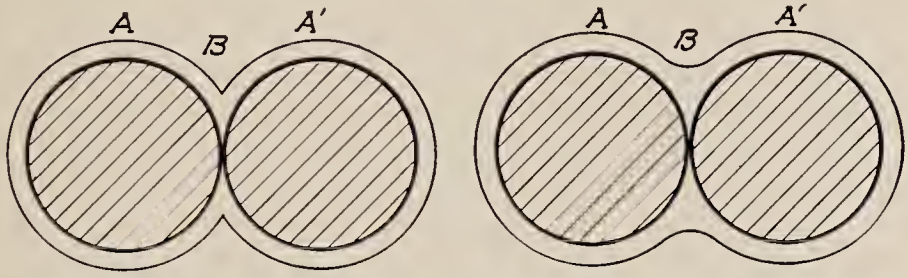


FIG. 28.—A conventional diagram showing the coalescence and readjustment of the outer capillary water film of two particles when brought in contact. At the left is shown the condition before the adjustment with a sharp angle at B; on the right, the films are at equilibrium with a thickening at B due to movement from A and A'.

as the outer capillary water is concerned. Complete equilibrium is probably never reached, however, due to constantly disturbing factors.

90. The determination of the amount of capillary water in the soil.—The capillary water in a sample of field soil may be determined by making a moisture test in the ordinary way for the total water contained,[1] after the gravi-

[1] A moisture determination on a sample of field soil is generally carried out as follows:—100 grams of the sample, after thorough mixing, is weighed into a suitable weighing dish and air-dried. The sample is then placed in an oven and heated at 100°C or 110°C for four or five hours. It is then cooled in a disiccator and weighed. The loss in weight is water. The moisture is calculated as percentage based on the dry matter of the soil. If the weight of the water lost was 20 grams, the percentage of moisture would be $(20 \div 80) \times 100$ or 25 per cent based on dry soil.

tational water has had time to drain away. This represents the hygroscopic plus the capillary water. A determination of the hygroscopic coefficient on another sample yields a figure which, when subtracted from the total water, will give the capillary water present in the soil. The capillary water at various points in a soil column may be obtained by subtracting the hygroscopic coefficient from the various percentages of moisture present, since the hygroscopic moisture is little influenced by height of column or ordinary structural conditions.

The determination cited above may or may not give the maximum water-holding capacity of a soil. To fill such a need a laboratory method has been devised by Hilgard,[1] which attempts to show the *maximum retentive* power of a soil for water.

A small perforated brass cup is used, having a diameter of about 5 centimeters and capable of containing a soil column 1 centimeter in height. A short column is used, since it is only under such conditions that a soil may retain against gravity the greatest amount of water. Also the soil is able to expand or contract, as the case may be, on the assumption of water until an equilibrium is reached. A filter-paper disc is often placed in the metal cup, and the soil is poured in, gently jarred down, and stroked off level with the top of the cup. The cup is then set in water and the soil is allowed to take up its maximum moisture. After draining, the weight of the wet soil plus the cup, together with the weights previously obtained, will allow a calculation of the total water retained based on the absolutely dry soil. If the maximum capillary water is desired, the hygroscopic coefficient may be subtracted from the maximum water retained.

Since this method is a laboratory procedure and the soil used is not in its normal structural state, the results cannot be accurately applied to field conditions. While the figures

[1] Hilgard, E. H., *Soils*, p. 209, New York, 1911.

obtained may be fairly accurate for a sand, they are certainly much too high for heavy soils. Comparisons with field soils have shown the data obtained by the above method to be from 30 to 130 per cent. too high.[1]

91. The capillary capacity of soils.—As might naturally be expected, the factors that tend to vary the amount of capillary water in a soil are several and their study is rather complex due to the secondary influences that they may generate and to the variable nature of the capillary moisture. These factors may be discussed under four heads: (1) surface tension, (2) texture, (3) structure and (4) organic matter.

Any condition that will influence surface tension will obviously influence the forces active in the outer portion of the capillary water. A rise in temperature, for example, if the soil is capillarily saturated, will allow some of the water to become gravitational. A lowering of temperature would cause an opposite change. This theory has been verified by certain experiments by King,[2] in which he found, other conditions being constant, a very decided influence on capillary water through change of temperature. Wollny[3] has shown that a depression of .65 per cent. in sand to as high as 3.7 per cent. in kaolin may occur from a rise in temperature of twenty degrees. While surface tension may be greatly varied by the presence of salts in solution, the soil-water is generally so dilute that the condition is not very important[4] in determining

[1] Alway, F. J., and McDole, G. R., *The Relation of Movement of Water in a Soil to its Hygroscopicity and Initial Moistness;* Jour. Agr. Res., Vol. X, No. 8, pp. 391-428, 1917.

Israelson, O. W., *Studies on Capacities of Soils for Irrigation Water;* Jour. Agr. Res., Vol. XIII, No. 1, pp. 1-36, 1918.

[2] King, F. H., *Fluctuations in the Level and Rate of Movement of Ground Water;* U. S. Dept. Agr., Weather Bur., Bul. 5, pp. 59-61, 1892.

[3] Wollny, E., *Untersuchungen über die Wasserkapacität der Bodenarten;* Forsch. a. d. Gebiete der Agri.-Physik, Band 9, Seite 361-378, 1886.

[4] Karraker, P. E., *Effect on Soil Moisture of Changes in the Surface Tension of the Soil Solution Brought About By Addition of Soluble Salts;* Jour. Agr. Res., Vol. 4, No. 2, pp. 187-192, May, 1915.

capillary capacity except in arid or semi-arid regions. In fact, changes in surface tension through any cause are of little practical importance.

The finer the texture of a soil the higher is its capillary capacity. This is due to the presence of colloidal material and to the greater number of angles in which capillary water may be held. The amount of internal surface exposed by a fine-textured soil is immensely larger than in one of a sandy character. While texture influences both the inner and outer capillary water the structure of the soil has more to do with the active film-like portion. As a clayey soil is granulated the interstitial spaces are enlarged and an increased capillary capacity results. At the same time, compacting a sand will cause a rise in the capillary capacity of that soil by increasing not only the actual effective surface, but also the number of angles possible for capillary concentration. Further compacting will then cause a decrease.

Organic matter, especially when well decayed, is commonly recognized as having great capillary capacity, far excelling the mineral portion of the soil in this respect. Its porosity affords an enormous internal surface, while its colloids exert an affinity for moisture which raises its water capacity to a very high degree. Its tendency to swell on wetting is but a change in condition incident to an approach to its maximum moisture content, and has a very marked influence on the structure of the soil. The water-holding capacity of muck and peat may range as high as 300 or 400 per cent. based on the dry matter present. Assuming a hygroscopic coefficient of 50 per cent., the capillary figure is still very high. Besides this direct effect, organic matter exerts a stimulus toward better granulation, a condition in itself favorable to increased water-holding power.

The capillary water in any soil, other conditions being equal, tends to vary with the height of the column. This comes about from the effect of gravity on the outer portion of the capillary

film, tending to give more water at the base of the column.

The condition may be explained empirically as follows: If a number of particles carrying maximum capillary films are brought together vertically, the weight of a large portion of the conducting film is thrown momentarily on the surfaces at the top. The capillary spaces at this point immediately lose water downward, so that they may assume a greater curvature and thus support this extra weight thrown on them. This curvature must be sufficient to balance the curvature pressure of the particles below plus the weight of the water in the connecting films. The particles beneath are at the same time undergoing a similar adjustment with a set of particles farther below, losing water in order to allow a change of curvature. The action continues in this manner in an attempt to establish equilibrium, thus giving more water at the bottom of the column. If the amount of capillary water is too great to be supported, enough is lost by gravity to bring about an equilibrium (see Fig. 29).

The above illustration, however, does not apply strictly to soil conditions, since only part of the capillary water is in a true film form and free to move with extreme ease. Moreover, rain water is applied from above, where also occurs rapid evaporation. Thus at any particular time the moisture content of a field soil might be higher near the surface than farther down in the soil

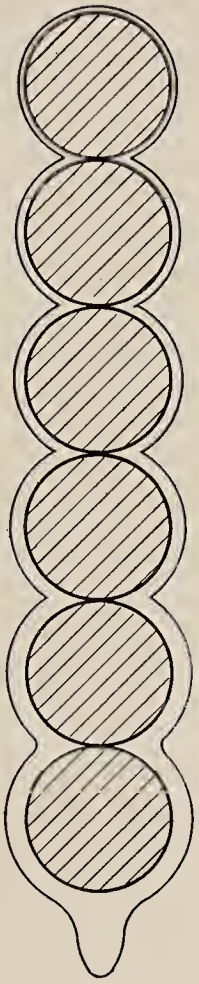


FIG. 29.—Diagram showing in a conventional way the adjustment tendency of the outer capillary water in a long column and the appearance of free water if the weight is too great.

or *vice versa* as the case may be. As the capillary water in a soil is reduced there is a tendency for the soil column to be more nearly uniform, providing, of course, that the equilibrium forces have had time to act and are not too much influenced by other factors.

While representative data regarding the moisture-holding capacity of soils are difficult to give, the following figures from Alway[1] indicate the general effect of texture and organic matter. The maximum water capacity was determined in the laboratory and the maximum field capacity was obtained by sampling the soils very shortly after irrigation.

TABLE XXXI

THE MAXIMUM WATER CAPACITY OF VARIOUS SURFACE SOILS AS DETERMINED IN THE LABORATORY AND UNDER FIELD CONDITIONS, RESPECTIVELY [2]

Soils	Organic Matter %	Hygroscopic Coefficient %	Field Water Capacity %	Maximum Water Capacity, Laboratory Method %
Sand	—	1.1	11.7	37.0
Sand	—	1.7	12.8	27.1
Sandy soil, residual	1.22	3.3	19.6	34.2
Red loam, residual	1.07	10.0	31.5	49.0
Silt loam, loess	1.55	10.1	31.3	56.8
Silt loam, loess	4.93	10.2	39.2	60.9
Black adobe	2.22	12.9	47.6	60.3

The effect of texture on water capacity is very apparent, a rough correlation existing also between the water retained and the hygroscopic coefficient. The influence of organic matter

[1] Alway, F. J., and McDole, G. R., *The Relation of Movement of Water in a Soil to its Hygroscopicity and Initial Moistness;* Jour. Agr. Res., Vol. X, No. 8, pp. 391-428, 1917.

[2] Note again that moisture percentages are always expressed on dry-soil weight.

is clearly shown by the two loess silt loams. Perhaps most important of all is the marked discrepancy between the actual field capacity and the arbitrary and artificial laboratory method. The normal water-holding capacity of a mineral soil, varying with texture and organic matter, seems to range from

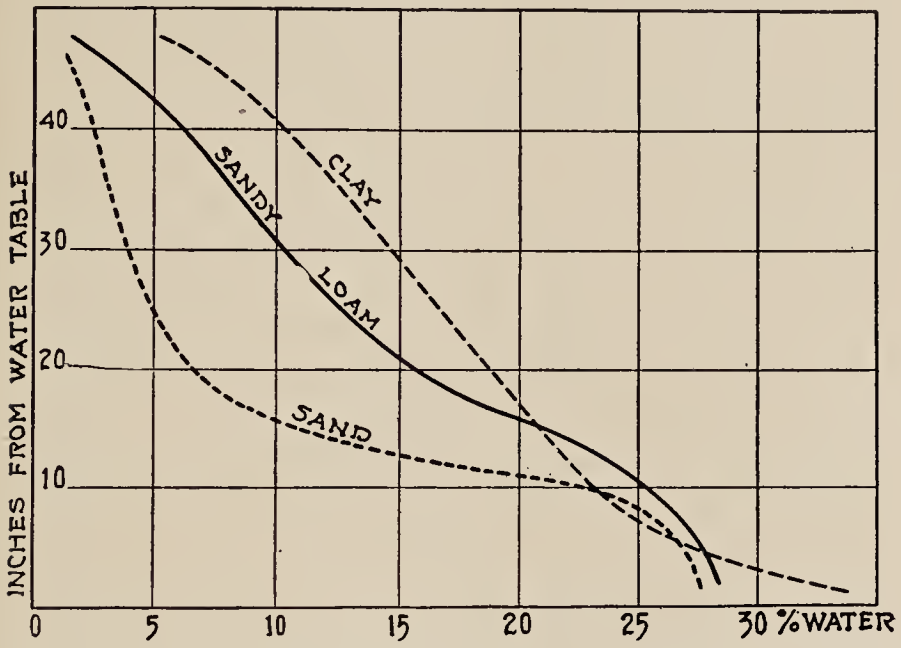


FIG. 30.—Diagram showing the distribution of moisture in capillary columns of soil of different textures. The end of each column rests in free water. (Buckingham, E., Bur. Soils, Bul. 38, 1907.)

about 10 to 50 per cent. based on dry soil. Muck and peat of course run much higher, 400 per cent. being not uncommon.[1]

[1] Briggs and McLane have perfected a method of comparing soils on the basis of their capacity to hold water against a definite and constant centrifugal force of one to three thousand times the force of gravity. The soils, in thin layer, are placed in perforated brass cups which fit into a centrifugal machine capable of developing the above force, and are whirled until equilibrium is reached. The resultant moisture percentage is designated as the *moisture equivalent*. It really represents the capillary capacity of a soil of minimum column length when subject to a constant and known force or pull. The finer the soil, the greater of course is the moisture equivalent. The authors found that 1 per cent. of clay or organic matter represented a retentive power of about .62

92. Capillary movement of water.—It has already been shown that different thicknesses of capillary films tend to equalize in the soil due to the pulling forces developed by the angle of curvature between the particles.[1] It is evident that differences in curvatures must be the motive force in the capillary movement of soil-water. Let it be supposed, for convenience, that three equal spheres when brought in contact contain unequal amounts of water in the angles of curvature (see Fig. 31). In this case the greater pull would exist at A, since the angle here is more acute. Consequently water must move

per cent., while 1 per cent. of silt corresponded to a retention of only .13 per cent. of water. Representative data is as follows:

Soils	Organic Matter %	Sands %	Silt %	Clay %	Moisture Equivalent %
Norfolk coarse sand...	.9	87.9	7.3	4.8	4.6
Norfolk fine sandy loam.	1.3	73.4	18.1	8.5	6.8
Yazoo loam.....	1.3	25.8	64.1	10.1	18.9
Waverly silt loam.....	2.0	14.9	62.9	22.2	24.4
Houston clay loam....	3.7	30.9	42.5	26.6	32.4
Houston clay.....	1.4	10.0	56.6	33.4	38.2

Briggs, L. J., and McLane, J. W., *The Moisture Equivalent of Soils;* U. S. Dept. Agr. Bur. Soils, Bul. 45, 1907.

[1] An ingenious method for measuring quantitatively the capillary pull exerted by a moist soil has been devised by Lynde and Dupré. The apparatus consists of a glass funnel joined to a thick-walled capillary tube by means of a piece of rubber tubing, a water seal being used at this point. The lower end dips into mercury. The soil to be studied is placed in the funnel, and after being saturated is connected by means of a wick of cheesecloth or filter paper to the water column previously established in the capillary tube. If no break occurs between the soil and the capillary water column, the apparatus is ready for use.

The excess water having drained away, there is a thinning of the films on the soil surface due to evaporation. Equilibrium adjustments now take place, which result in the drawing upward of the water column. The mercury follows, and the strength of the pull may be measured by the length of the mercury column. The old method of measuring capillary power by the water movement through a dry soil is vitiated by two conditions—the length of time necessary, and the fact that the maximum lift cannot be obtained due to excessive friction. This new method uses a wet soil, requires only a short time, and gives a more nearly accurate idea of the power of the capillary pull. It does not, however,

through the connecting film until the pull at A and that at B become the same. Such an adjustment might go on over a large number of films, and if one end of the column was exposed to an evaporation of just the correct rate and the other end was in contact with plenty of moisture, large quantities of water would be moved by capillarity.

This capillary movement may go on in any direction in the soil, since it is largely independent of gravity; yet under natural field conditions the adjustment tends to take place very largely in a vertical direction, due to evaporation and absorption by plants. When a soil is exposed to evaporation, the surface films are thinned and water moves upward to adjust the tension. This explains why such large quantities of soil-water may be lost so rapidly from an exposed soil. Capillary adjustment may go on downward, also, as is the case after a shower. Here the rapidity of the adjustment is aided by gravity and movement of the water of percolation.

The capillary adjustment in a soil tends to take place whether or not the soil column is in contact with free water. If no gravity water is present, the adjustment is merely from a moist soil to a drier one. In studying the rate and height of capillary movement of water in any soil, especially in the

yield data regarding rate of movement,—a factor of vital importance to plant growth.

Lynde and Dupré, in their results, confirm the statements already made regarding the relation of texture to capillary power:

Soil	Diameter of Grains in Millimeters	Lift of Water Column, in Feet
Medium sand	.50 - .25	.98
Fine sand	.25 - .10	1.78
Very fine sand	.10 - .05	4.05
Silt	.05 - .005	9.99
Clay	.005- —	26.80

Lynde, C. J., and Dupré, H. A., *On a New Method of Measuring the Capillary Lift in Soils;* Jour. Amer. Soc. Agron., Vol. 5, No. 2, pp. 107-116, 1913.

laboratory, the maintenance of a supply of free water is usually provided for, since this allows a nearer approach to the maximum capillary capacity for any point in the column and also gives the most rapid capillary adjustment.

To persons familiar with the habits of growing plants, it is evident that capillary movement must play an important part in their nutrition, since the rootlets are unable to bring their absorptive surfaces in contact with all the interstitial spaces in which the bulk of the available water is held. Consequently a consideration of the movement of capillary mois-

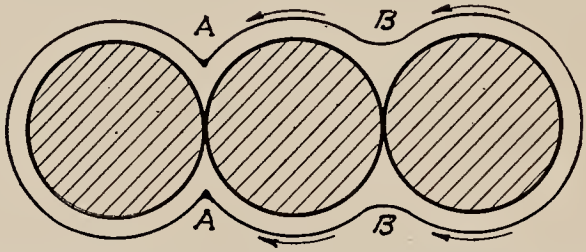


FIG. 31.—Conventional diagram showing the mechanics of the movement of the film portion of the capillary water. The readjustment takes place in the direction of (A) due to the tension developed by the greater film curvature at that point.

ture is necessary, not only as to its mechanics, but also in respect to the factors influencing its rate and height of movement. These factors are as follows: (1) surface tension and viscosity; (2) thickness of capillary film; (3) texture; and (4) structure.

Surface tension and viscosity.—As the force developed by surface tension is the activating factor in capillary adjustment, any change in the former will influence this movement. Theoretically, a rise in temperature or the presence of soluble salts would decrease the rapidity of the capillary activity of soil-water. In a normal soil, however, the change of surface tension is generally not sufficient to have any very great practical influence. Viscosity, on the other hand, is much more important. If the viscosity of water at 0° C. is taken as 100,

its viscosity at 25° is 50 and at 30°, 45. This explains to a large degree the increased rate of capillary movement due to temperature rise.[1] The distance of such adjustment would, however, be lessened somewhat. Salts in solution would tend to check the rate of capillary movement both through increased viscosity and the influence on surface tension.[2] It would only be in alkali soils, where the concentration of soluble salts is very great, that any considerable retardation would occur.

Thickness of capillary film.—It has been repeatedly noticed, in the study of the capillary adjustment between two soils that the lower the percentage of water, the slower is the movement. This indicates that the thickness of the outer capillary film, which connects the interstices in which lies the bulk of the movable soil-water, is an important factor in the rate of movement.

The above phenomena may be empirically explained as follows: Let it be supposed that a withdrawal of water occurs at A (see Fig. 32), the interstitial space between two of the particles, the water surface being represented by the line aa′. There is an immediate increase in the curvature of this surface, and water tends to flow through the capillary film channel (cc′c″) toward this area of greater tension. If water

[1] Bouyoucos has shown that the movement in a soil column of uniform moisture is from the warmer portion toward the colder. The movement from a moist layer to a dryer one goes on more rapidly than when the moist soil is cool and the dry soil warm. Bouyoucos, G. J., *Effect of Temperature on Movement of Water Vapor and Capillary Moisture in Soils;* Jour. Agr. Res., Vol. V, No. 4, pp. 141-172, Oct., 1915.

[2] Wollny, E., *Untersuchungen über die Kapillare Leitung des Wassers in Boden.* Forsch. a. d. Gebiete d. Agr.-Physik, Band 7, Seite 269-308, 1884. Also, Forsch. a. d. Gebiete d. Agri.-Physik, Band 8, Seite 206-220. 1885.

Briggs, L. J., and Lapham, M. H., *Capillary Studies;* U. S. Dept. Agr. Bur. Soils, Bul. 19, pp. 5-18, 1902.

Karraker, P. E., *Effect on Soil Moisture of Changes in the Surface Tension of the Soil Solution brought about by the Addition of Soluble Salts;* Jour. Agr. Res., Vol. IV, No. 2, pp. 187-192, May, 1915.

Davis, R. O. E., *The Effect of Soluble Salts on the Physical Properties of Soils;* U. S. Dept. Agr. Bur. Soils, Bul. 82, pp. 23-31, 1911.

continues to be withdrawn at A, this adjustment goes on with considerable ease until the film channel (cc′c″) becomes so thin as to cause its surface now (bb′b″) to approach very closely to the surface of the soil particle and the inner capillary water. The sluggishness of the water movement becomes a factor at this point, impeding the capillary adjustment toward A. This point of sluggish capillary movement has been designated by Widtsoe[1] as the point of *lento-capillarity,* and

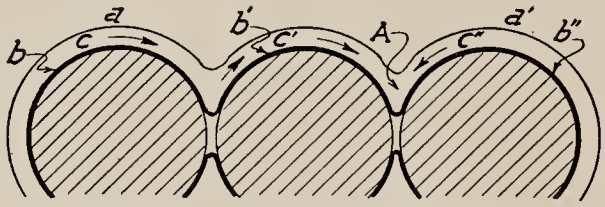


FIG. 32.—Conventional diagram for the explanation of the effect of the thickness of water film about the soil particles and their colloidal complexes on the ease of capillary adjustment.

is expressed in percentage based on the dry weight of the soil. It lies near the transition zone between the inner and outer capillary water.

The amount of capillary water delivered at any one point, therefore, will obviously be influenced by the thickness of the film and may consequently be taken as a measure of rate of adjustment. A short soil column should deliver more water than a longer one, due to the thicker films at the surface of the former. King,[2] in studying the evaporation from the surfaces of sand columns of different lengths, their bases being in contact with free water, obtained some significant data.

[1] Widtsoe, J. A., and McLaughlin, W. W., *The Movement of Water in Irrigated Soils;* Utah Agr. Exp. Sta., Bul. 115, pp. 223-231, 1912.

[2] King, F. H., *Principles and Conditions of the Movements of Ground Water;* U. S. Geol. Survey, 19th Ann. Rept., Part II, p. 92, 1897-1898.

Also Briggs, L. J., and Lapham, M. H., *Capillary Studies;* U. S. Dept. Agr. Bur. Soils, Bul. 19, pp. 24-25, 1902.

He found, for example, that a six-inch column would deliver six times more water to its surface in a given time than a thirty-inch column operating under the same conditions.

In air-dry soil it is obvious that, before capillarity may function, a continuous film must be present. Such a condition is impossible unless some of the more active capillary moisture is in the soil. The water content in a soil must often be rather high before capillarity is a noticeable phenomenon. This condition is taken advantage of in the use of soil-mulches, where a loose dry layer of soil on the surface may check evaporation by impeding capillary rise. The presence of oily substances on the soil grains may also be of some importance in this respect.

Texture.—In soils of fine texture not only is the amount of film surface exposed greater than in coarse soils but the curvature of the films is also greater, due to the shorter radii. The effective pressure exerted by the films is consequently much higher in fine-grained soil. Both the greater exposure of surface and the increased pressure serve to raise the friction coefficient and retard the rate of flow. The finer the texture of the soil, other factors being equal, the slower is the movement of capillary water. Water should, therefore, rise less rapidly from a water-table through a column of clay than through a sand or a sandy loam.

The distance to which water may be drawn by the effective capillary power of a soil, equilibrium being established, depends on the number of interstitial angles. The greater the number of angles, the greater is the total pulling power of the films. As a silt soil contains a larger number of such angles, its capillary pull is greater than that of sand, and consequently the ultimate movement would be of greater scope. The finer the texture, then, the slower is the rate of capillary movement but the greater is the distance.

The relation of texture to rate and height of capillary movement in air-dry soil is shown by the following unpublished

data, obtained in the laboratory of the Department of Soil Technology, Cornell University:

TABLE XXXII

EFFECT OF MOISTURE ON RATE AND HEIGHT OF CAPILLARY RISE FROM A WATER-TABLE THROUGH AIR-DRY SOIL

SOIL	1 HOUR	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS
	INCHES	INCHES	INCHES	INCHES	INCHES	INCHES
Sandy soil.....	3.5	5.0	5.9	6.8	6.8	6.9
Clayey soil.....	.5	5.7	8.9	10.9	12.2	13.3
Silt loam.....	2.5	14.5	20.6	24.2	26.2	27.4

It is seen that the movement in sand is rapid, one-half of the total rise being attained in one hour. The maximum height is reached in about three days. The silt loam in this case seems to be of just about the proper textural condition for a fairly rapid rise, yet it exerts enough capillary pull to attain a good distance above the water-table. The friction in the clay is greater, however, and this results in a slower rate.

Structure has already been shown to affect capillary capacity by its influence on the angle interstices and the closeness of the contacts. Evidently, therefore, it may alter both the rate and the height of capillary rise. The loosening of a clay soil or the compacting of a sandy soil will lessen the effective film friction, while at the same time it may strengthen the capillary pull resulting in a faster and a higher capillary flow of water. What may be the best structural condition of any soil in which this result is realized to its highest degree can not be predicted exactly. In general, however, this point is approached when the soil is in the best physical condition for crop growth. Tillage operations, tile drainage, and the addition of lime and organic matter operate toward this result by their granulating tendencies; while rolling, by compacting a

too loose surface, may accomplish the same effect but by an opposite process.

At certain seasons of the year capillarity should be impeded near the surface, as it continually carries valuable water upward to be lost by evaporation. This movement may be checked somewhat by producing on the soil surface, by appropriate tillage, a layer of dry, loose soil. This layer, called a *soil-mulch,* resists wetting because of its dryness, while at the same time it affords but little surface and few angle interstices for effective capillary pull. Moisture also moves very slowly from a moist, cool soil to a dry, warm one.[1] Thus it is that a farmer, in order to meet immediate or future plant needs, may alter and control capillary movement by careful attention to physical conditions, especially those at the surface where evaporation is always active.

93. Gravitational water and its movement.—As soon as the capillary capacity of a soil column is satisfied, further addition of moisture will cause the appearance of free water in the air spaces. By the attraction of gravity, this water moves forward through the soil at a rate varying with conditions. In general, the flow is governed by four factors—pressure, temperature, texture, and structure. An understanding of the operation of these forces is important, since the rapid elimination of free water from the soil is necessary for normal plant growth.

It is very evident that any pressure exerted on a water column will alter the rate of flow. Under normal conditions pressure may arise from two sources, atmospheric pressure and the weight of the water column. Changes in barometric pressure are communicated to gravitational water through a movement of the soil-air. As the mercury column rises more air is forced into the soil and the pressure on the soil-water

[1] Bouyoucos, G. J., *Effect of Temperature on Movement of Water Vapor and Capillary Moisture in Soils;* Jour. Agr. Res., Vol. V, No. 4, pp. 141-172, Oct., 1915.

increases. The weight of the free water column may also have some influence. Although King[1] and Welitschkowsky[2] have shown that definite relationships exist between the movement of gravity water and both atmospheric pressure and weight of water column, the practical field importance of these factors are rather slight.

A rise in temperature of the soil not only varies the relative amounts of capillary and free water present, but at the same time it increases the fluidity and thus facilitates percolation. The expansion of the soil-air also tends to increase such movement. On the other hand the swelling of hydrogels which may be present tends to impede percolation to such an extent that the movement of free water through a heavy soil is often markedly checked by temperature rise.

Of much more practical importance than either pressure or temperature in the flow of gravity water is the texture and the structure of the soil. In working with sands of varying grades, Welitschkowsky,[3] Wollny,[4] and others have shown that the flow of water varies with the size of particle, or texture. King[5] has demonstrated that in general the rate of flow through such is directly proportional to the square of the diameter of the particles. By the use of the effective mean

[1] King, F. H., *Principles and Conditions of the Movements of Ground Water;* U. S. Geol. Survey, 19th Ann. Rep., Part II, pp. 67-206; 1897-1898.

King, F. H., *The Soil,* p. 180, New York, 1906.

[2] Welitschkowsky, D. von., *Experimentelle Untersuchungen über die Permeabilität des Bodens für Wasser;* Archiv. f. Hygiene, Band II, Seite 499-512. 1884.

Wollny, E., *Untersuchungen über die Permeabilität des Bodens für Wasser;* Forsch. a. d. Gebiete d. Agr.-Physik, Band 14, Seite 1-28, 1891.

[3] Welitschkowsky, D. von., *Experimentelle Untersuchungen über die Permeabilität des Bodens für Wasser;* Archiv. f. Hygiene, Band II, Seite 499-512, 1884.

[4] Wollny, E., *Untersuchunger über den Einfluss der Struktur des Bodens auf dessen Feuchtigketis—und Temperaturverhaltnisse;* Forsch. a. d. Gebiete d. Agr.-Physik, Band 5, Seite 167, 1882.

[5] King, F. H., *Principles and Conditions of the Movements of Ground Water;* U. S. Geol. Survey, 19th Ann. Rep., Part II, pp. 222-224, 1897-1898.

diameter of a sand sample he was able to calculate a theoretical flow which compared very closely to observed percolations. In sandy soils low in organic matter this law holds in a very general way, but in clays it fails entirely. For example, if such a law was in force a sand having a diameter of .5 millimeter would exhibit a flow 10,000 times greater than that through a clay loam with a diameter, say, of .005 millimeter; whereas the actual ratio, as observed experimentally by King, was less than 200. Such a discrepancy is to be expected as it is impossible accurately to apply mathematics to soils carrying any appreciable amount of colloidal matter.

Evidently, therefore, while it can be stated as a general thesis that the flow of gravity water varies with the texture, being much more rapid through a coarse than through a fine soil, no law can be deduced for soils, since structure exerts such a modifying influence. The percolation in a heavy soil takes place largely through lines of seepage, which are really large channels developed by various agencies. If in the drainage of average soil, the farmer depended on the movement of water through the individual pore spaces, the soil would never be in condition for crop growth. These lines of seepage are developed by the ordinary forces that function in the production of soil granulation, as freezing and thawing, wetting and drying, lime, organic matter, roots, and tillage operations.

94. Determination of the quantity of free water that a soil will hold.—While there is no particular advantage in finding the quantity of gravitational water that a soil will hold, since a normal soil should never remain saturated for any length of time, it is nevertheless of interest to know by what means such data may be obtained. One method is to saturate a soil column of known weight, and then, by exposing it to percolation, measure the amount of water that is lost. The gravitational water can then be expressed in terms of dry soil.

As valuable a figure may be obtained by calculation, providing the specific gravity and volume weight of the soil is known together with its percentage of moisture based on dry weight when it is capillarily satisfied. The following formulæ [1] may be used:

1. Percentage pore space $= 100 - \left[\frac{\text{vol. wt.}}{\text{sp. gr.}} \times \frac{100}{1}\right]$

2. Percentage free water (based on dry weight of soil) $= \frac{\%\ \text{Pore Space}}{\text{Vol. Wt.}} - \%$ water at maximum capillarity

Suppose, for example, that a sand with a specific gravity of 2.6 and a volume weight of 1.56 contains 20 per cent. of water when at its maximum retentive power. Its pore space would be 40 per cent. If this pore space were filled with water, the soil would contain 25.6 per cent. based on the dry weight of the soil (per cent. pore space ÷ vol. wt.). If the total capacity of the soil for water is 25.6 per cent. and the hygroscopic plus the capillary capacity is 20 per cent., the free water must be 5.6 per cent.[2]

95. Importance of the study of the flow and composition of drainage water.—A clear understanding of the factors governing the flow of gravitational water is of special importance in tile drainage operations, particularly regarding the depth of and interval between tile drains. Since percolation is so slow in a heavy soil it is evident that the tile must be near the surface in order to secure efficient drainage. In a sand the depth may be increased, because of the slight re-

[1] Percentage of pore space represents the percentage of water by volume that would occupy such a space. Percentage of water by volume divided by volume weight gives percentage of water based on dry weight of soil. Conversely, multiplying percentage of moisture calculated on dry weight of soil by volume weight will give percentage of water by volume.

The air space in a soil at any particular moisture content may be calculated as follows:

Percentage of air space $=$ % pore space $-$ (%H_2O $\times$ Vol. Wt.)

[2] Below will be found some generalized moisture data on two distinct

sistance offered to water movement. The depths for laying tile in a heavy soil range from one and a half to two and a half feet, while in a sand the tile may often be placed as deep as four feet below the surface. It is evident also that the less deep a tile drain is laid the less distance on either side it will be effective in removing the water; consequently on a clay soil the laterals must be relatively close as compared to the interval generally recommended for a sandy soil. A rational understanding of the movements of gravitation water is clearly necessary in the installation of tile drains not only that the system may be efficient, but also that a minimum effective cost may be realized.[1]

The water lost from the soil by drainage is of especial interest in plant production because of the large amounts of nutrient elements carried away each year. Such loss is particularly important in regard to the lime and nitrogen.[2] The equivalent of approximately 500 pounds of sodium nitrate and 1000 pounds of calcium carbonate have been known to leach from an acre of bare soil every year under humid conditions.

classes of soils. As usual, all of the moisture data is expressed as percentage based on absolutely dry soil.

	Sandy Soil	Clayey Soil
Specific gravity	2.67	2.65
Volume weight	1.60	1.20
Pore space	40.0%	54.8%
Hygro. coefficient	1.0%	10.0%
Optimum moisture (average)	10.0%	30.0%
Maximum field capacity	17.0%	44.0%
Air space at hygro. coefficient	38.4%	42.8%
Air space at opt. moisture	24.0%	18.7%
Air space at max. field capacity	12.8%	1.9%
Possible free water	8.0%	1.6%

See Kopecky, J., *Die physikalischen Eigenschaften des Boden;* Internat. Mitt f. Bodenkunde, Bd. IV, Heft 2-3, Seite 138-180. 1914.

[1] For a more complete discussion of tile drains, see Chap. X, paragraph 110.

[2] Lyon, T. L., and Bizzell, J. A., *Lysimeter Experiments;* Cornell Univ. Agr. Exp. Sta., Memoir 12, June, 1918.

Two methods of procedure are available for the study of drainage problems—the use of an efficient system of tile drains, and the construction of lysimeters. For the first method an area should be chosen where the tile drain receives only the water from the area in question and where the drainage is efficient. A study of the amounts of flow throughout a term of years will yield much valuable data concerning the factors already discussed. An analysis of the drainage water will throw light on the ordinary losses of plant nutrients from a normal soil under a known cropping system. The advantage of such a method of attack lies not only in the fact that a large area of undisturbed soil is considered, but also in the opportunity to study practical field treatments in relation to the movement and composition of drainage water.

The lysimeter method, however, has been the usual mode of approaching such problems. In this method a small block of soil is used, being entirely isolated by appropriate means from the soil surrounding it. Effective and thorough drainage is provided. The advantages of this method are that the variations in a large field are avoided, the work of carrying on the study is not so great as in a large field, and the experiment is more easily controlled. One of the best-known sets of lysimeters is that at the Rothamsted Experiment Station[1] in England. Here blocks of soil one one-thousandth of an acre in surface area were isolated by means of trenches and tunnels, and, supported in the meantime by perforated iron plates, were permanently separated from the surrounding soil by masonry. The blocks of soil were twenty, forty, and sixty inches in depth, respectively. Facilities for catching the drainage were provided under each lysimeter. The advantages of such a method of construction lies in the fact that the structural condition of the soil is undisturbed and consequently the data are immediately trustworthy.

[1] Lawes, J. B., Gilbert, J. H., and Warington, R., *On the Amount and Composition of the Rain and Drainage Waters Collected at Rothamsted;* Jour. Roy. Agr. Soc., Ser. II, Vol. 17, pp. 269-271, 1881.

At Cornell University[1] a series of cement tanks sunk in the ground have been constructed. Each tank is about four feet and two inches square and about four feet deep. A sloping bottom is provided, with a drainage channel opening into

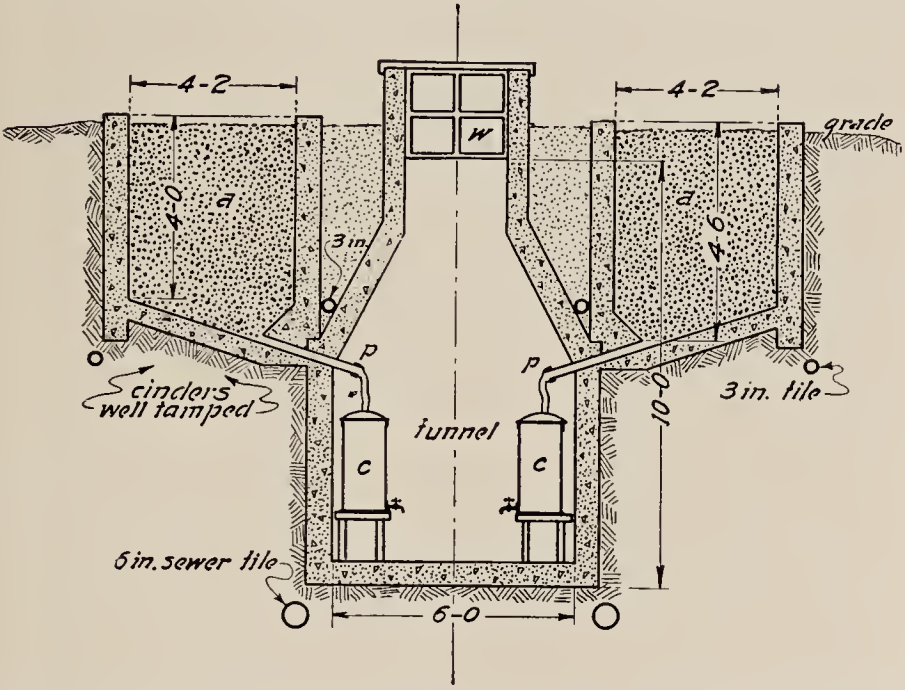


FIG. 33.—Cross section of the lysimeter tanks at Cornell University, Ithaca, New York. Each tank is one of a series, one tunnel serving the two rows. Dimensions are given in feet and inches. Soils under investigation (a), outlet (p), can for catching drainage water (c) and sky-light (w).

a tunnel beneath and at one side. As the tanks are arranged in two parallel rows, one tunnel suffices for both. (See Fig. 33.) The sides of the tanks are treated with asphaltum in

[1] Lyon, T. L., *Tanks for Soil Investigation at Cornell University;* Science, N. Ser., Vol. 29, No. 746, pp. 621-623, 1909.

There are other types of lysimeters. See, for example, Mooers, C. A., and MacIntire, W. H., *Two Equipments for Investigation of Soil Leachings: I. A Pit Equipment. II. A Hillside Equipment;* Tenn. Agr. Exp. Sta., Bul. 111, 1915.

MacIntire, W. H., and Mooers, C. A., *A Pitless Lysimeter Equipment;* Soil Sci., Vol. XI, No. 3, pp. 207-209, Mar., 1921.

order to prevent solution. The soil must of course be placed in the tanks, this causing a disturbance of its structural condition. As a consequence, data as to rate of flow and composition of the drainage water are rather unreliable for the first few years. Such an experiment must necessarily be of considerable duration.

96. Thermal movement of water.—Little has been said as yet regarding this mode of water movement, the vapor flow, which is not peculiar to one form of soil-water but affects them all. It is at once apparent that the movement of water-vapor can be of little importance within the soil itself, since it depends so largely on the diffusion and convection of the soil-air. While the soil-air is no doubt practically always saturated with water-vapor, the loss of moisture by this means is slight. Buckingham [1] has shown that, while sand allows such a movement to the greatest degree, the loss through any appreciable depth of layer is almost negligible. The question of the thermal movement of water at the soil surface, however, is vital in farming operations. At this point the moisture is exposed to sun and wind, and drying goes on rapidly, the free, capillary, and a part of the hygroscopic water vaporizing in the order named. If the loss of the moisture in the surface layer of soil was the only consideration, the problem would not be serious; but the movable water of the whole soil section must be considered also. As the films at the surface become thin, a capillary movement begins, and if the evaporation is not too rapid a considerable loss of water may occur in a short time. The moisture thus lost is that of most value to plants. The evaporation from the bare soil in the Rothamsted lysimeters[2] averaged about seventeen inches a year, with

[1] Buckingham, E., *Studies on the Movement of Soil Moisture;* U. S. Dept. Agr. Bur. Soils, Bul. 38, pp. 9-18, 1907.

See also Bouyoucos, G. J., *Effect of Temperature on Movement of Water Vapor and Capillary Moisture in Soils;* Jour. Agr. Res., Vol. V, No. 4, pp. 141-172, Oct., 1915.

[2] Warington, R., *Physical Properties of the Soil,* p. 109; Clarendon Press, Oxford, 1900.

a rainfall ranging from twenty-two to forty-two inches. This means that from one-third to one-half of the effective rainfall was entirely lost as thermal water. The necessity of checking such a loss becomes apparent, especially in regions where rainfall is slight or drought periods are likely to occur. As no country is free from one or the other of such contingencies, the great prominence that methods of moisture conservation hold in systems of soil management is understandable. While means of checking losses by leaching and run-off are advocated, effective retardation of surface evaporation is always emphasized.

CHAPTER IX

THE WATER OF THE SOIL IN ITS RELATION TO PLANTS

Water begins its service to plants by promoting the processes of soil weathering, which results in the simplification of compounds for plant utilization. It also functions more directly in plant development in maintaining the turgidity of the cells, in carrying materials, regulating temperature and in furnishing a supply of hydrogen and oxygen for the plant. These direct and indirect functions of water in relation to plant growth may be considered from a number of different viewpoints.

97. Functions of water to plants.—Water acts as a solvent and as a medium for the transfer of nutrients from the soil to the plant. This transfer relationship is rather complex, since most nutrient materials penetrate the cell-walls of the absorbing surfaces of the roots in an ionic condition. As a nutrient water becomes a part of the cell contents without change or is broken down into its elements and utilized in the production of new compounds. In addition, water by maintaining turgidity, in equalizing the temperature by evaporation from the leaves, and in facilitating quick shifts of nutrients and food from one part of the plant to another, acts as a carrier during assimilation and while synthetic and metabolic processes are going on.

Soil-moisture, therefore, in proper amounts, becomes one of the controlling factors in crop growth and must be looked to before the maximum utilization of the nutrient elements can be expected. The amount of water held within the plant

is not large, however, in comparison with the amount lost by transpiration, although green plants contain from 60 to 90 per cent. of moisture.

Because of the readiness with which moisture passes from plants into the atmosphere, large quantities must be taken

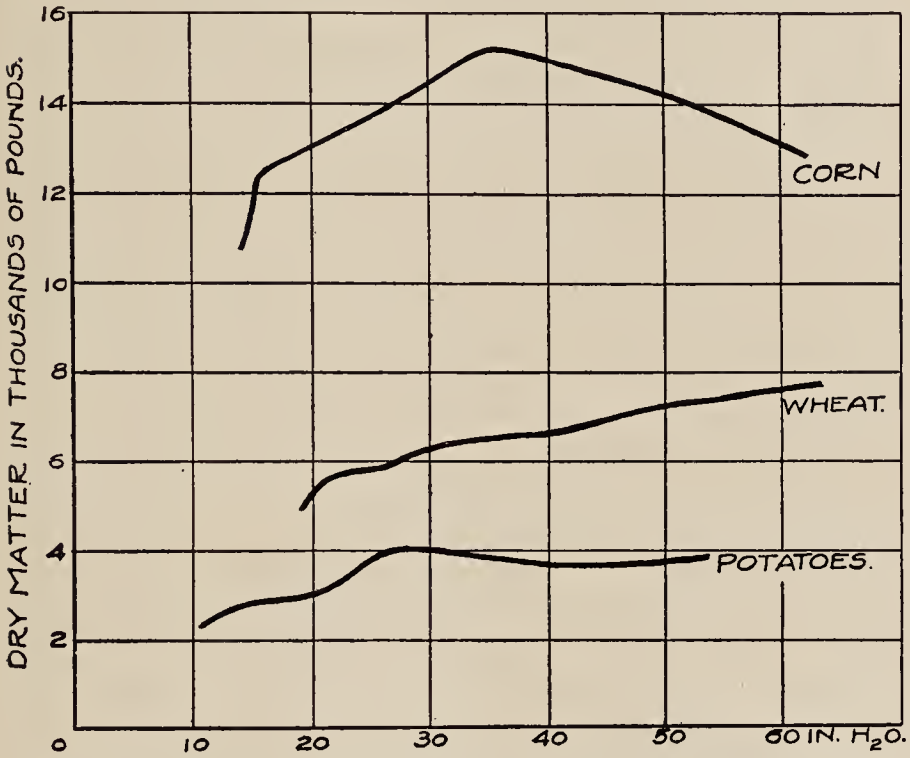


FIG. 34.—The effect of increasing water supply on the production of dry matter in various crops. The water is expressed in acre-inches.

from the soil in order that the plant may maintain its proper turgor. That the crop may be properly supplied with water, optimum moisture conditions should prevail in the soil at all times during the growing season. It must not be inferred that loss through the plant is the only means by which moisture leaves the soil, since drainage and evaporation are by no means insignificant factors.

98. Influence of water on the plant.[1]—As the amount of water available to a crop is increased up to a certain point, the vegetative growth also is usually increased, the plant becoming more succulent. The percentage of moisture in the crop, even at harvest time, is usually high. Shipping qualities are depressed with increased moisture, especially if the water available is excessive. With an enlargement of the plant cell a change probably occurs in the cell contents, tending toward a greater susceptibility to disease.

Ripening especially is delayed by large amounts of moisture, tillering is diminished, and the percentage of protein content of the crop is decreased. It is a curious fact that many of the general and morphological effects of large quantities of available water on plant growth are the same as those caused by the presence of too much soluble nitrogen. In cereals the stimulation from a large supply of water is shown especially in the ratio of grain to straw. Widtsoe's[2] findings in this regard are representative of the data[3] available on this point:

TABLE XXXIII

DISTRIBUTION OF DRY MATTER BETWEEN GRAIN AND STRAW WITH VARYING AMOUNTS OF WATER.

Inches of water applied	5	7½	10	15	25	35	50
Grain in percentage of dry matter of entire crop	44	43	43	41	38	37	33

[1] Mitscherlich, E. A., *Das Wasser als Vegetationsfaktor;* Landw. Jahr., Band 42, Seite 701-717, 1912.

[2] Widtsoe, J. A., *The Production of Dry Matter with Different Quantities of Irrigation Water;* Utah Agr. Exp. Sta., Bul. 116, p. 49, 1912.

[3] Bunger, H., *Über den Einfluss Verschieden Hohen Wassergehalts des Bodens in den Einzelhen Vegetationsstadien bei Verschiedenem Nährstoffreichtum auf die Entwicklung des Haferpflanzen;* Landw. Jahrb., Band 35, Seite 941-1051, 1906.

Also, Seelhorst, C., von, und Freckmann, W., *Der Einfluss des Wassergehaltes des Bodens auf die Ernten und die Ausbilding Verschiedener Getriedevarietäten;* Jour. f. Landw., Band 51, Seite 253-269, 1903.

As a rule, this depression of the ratio of grain to straw is not due to an actual decrease in the grain, but to a correspondingly greater production of dry matter in the vegetative parts. As available water is augmented, the dry matter of plants increases until a maximum is reached. The general relationships are well exemplified by data from Widtsoe [1] (Fig. 34), although other equally valuable figures may be obtained from von Seelhorst [2] and Atterberg,[3] who have done much work on the subject.

99. The water requirements of plants.—As might be expected, the pounds of water transpired for every pound of dry matter produced in the crop is very large. This figure, called the *transpiration ratio,* or water requirement, ranges from 200 to 500 for crops in humid regions, and almost twice as much for crops in arid climates. An accurate determination of the transpiration ratio of a crop is somewhat difficult, due to the methods of procedure necessary and also to the difficulty of controlling the numerous factors that influence the transpiration. For really reliable figures the plants must be grown in cans or pots in order that the water lost may be determined accurately by weighing. If there is no percolation the water ordinarily lost from a cropped soil includes both that evaporated from the soil surface and that transpired from the leaves. The former loss may be controlled largely in one of two ways: (1) by covering the soil so that evaporation is absolutely checked and the only loss is by transpiration; or (2) by determining the evaporation from a bare pot and, by substracting this from the total water loss

[1] Widtsoe, J. A., *The Production of Dry Matter with Different Quantities of Irrigation Water;* Utah Agr. Exp. Sta., Bul. 116, pp. 19-25, 1912.

[2] Seelhorst, C., von, und Krzymowski, R., *Versuch über den Einfluss, welchen das Wasser in dem Verschiedenem Vegetationsstadien des Hafers auf sein Wachstum ausübt;* Jour. f. Landw., Band 53, Seite 357-370, 1905.

[3] Atterberg, A., *Die Variationem der Nährstoffgehalte bei dem Hafer;* Jour. f. Landw., Band 49, Seite 97-113, 1901.

from a cropped soil, finding the loss due to transpiration alone.

An objection to the former method is that any covering which interferes with evaporation interferes with proper soil aëration also and may render soil conditions abnormal. In the second method, however, an even more serious error enters, since the evaporation from the bare soil is not the same as that from a soil covered by vegetation because of the effect of shading. Moreover, due to the action of the roots, less water is likely to move to the surface by capillary attraction in the cropped soil. Therefore any data that may be quoted can be only general in its application, not only because of the errors of determination but also because of the great number of factors that under normal conditions may vary the transpiration ratio. The following data drawn from various investigators working by the general methods [1] already outlined, give some idea of the water transpired by different crops, due allowance being made for various disturbing factors. (See Table XXXIV, page 189.)

100. Factors affecting transpiration.[2] — It is obvious from the figures quoted that the transpiration ratio of a crop is the resultant of a number of influences.[3] The factors may be listed under three heads, as follows:

1. Crop.—Difference due to different crops and to variations of the same crop.

[1] A brief discussion of the various methods is found as follows: Montgomery, E. G., *Methods of Determining the Water Requirements of Crops;* Proc. Amer. Soc. Agron., Vol. 3, pp. 261-283, 1911.

Also Briggs, L. J., and Schantz, H. L., *The Water Requirement of Plants;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 285, 1913.

[2] Kiesselbach, T. A., *Transpiration as a Factor in Crop Production;* Nebr. Agr. Exp. Sta., Res. Bul. 6, June, 1916.

[3] A complete review of the literature concerning the climatic and soil factors in their effect on transpiration may be found as follows: Briggs, L. J., and Shantz, H. L., *The Water Requirement of Plants;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 285, 1913.

See also, Briggs, L. J., and Shantz, H. L., *Daily Transpiration during the Normal Growth Period and its Correlation with the Weather;* Jour. Agr. Res., Vol. VII, No. 4, pp. 155, 212, Oct., 1916.

TABLE XXXIV

WATER REQUIREMENTS OF PLANTS AS DETERMINED BY DIFFERENT INVESTIGATORS.

CROP	LAWES [1] HARPENDEN, ENGLAND, 1850	WOLLNY [2] MUNICH, GERMANY 1876	HELLRIEGEL [3] DAHME, GERMANY 1883	KING [4] MADISON, WIS., 1895	LEATHER [5] PUSA, INDIA 1911	BRIGGS AND SHANTZ [6] AKRON, COLO. 1911-1913
Barley ...	258	774	310	464	468	534
Beans	209	—	282	—	—	736
Buckwheat	—	646	363	—	—	578
Clover ...	269	—	310	576	—	797
Maize	—	233	—	271	337	368
Millet	—	447	—	—	—	310
Oats	—	665	376	503	469	597
Peas	259	416	273	477	563	788
Potatoes ..	—	—	—	385	—	636
Rape	—	912	—	—	—	441
Rye	—	—	353	—	—	685
Wheat ...	247	—	338	—	544	513

[1] Lawes, J. B., *Experimental Investigation into the Amount of Water Given off by Plants during their Growth;* Jour. Hort. Soc., London, Vol. 5, pp. 38-63, 1850. Pots holding 42 pounds of field soil were used. Evaporation from soil was reduced to a very low degree by perforated glass covers cemented on the pots. The figures quoted are from unfertilized soil.

[2] Wollny, E., *Der Einfluss der Pflanzendecke und Beschattung auf die Physikalischen Eigenschaften und die Fruchtbarkeit des Bodens,* Seite 125; Berlin, 1877. Wollny grew plants in sand in amounts ranging from 5 to 12 kilograms. Evaporation was reduced to a very low degree by perforated covers. Actual evaporation from uncropped cans was observed, however.

[3] Hellriegel, H., *Beiträge zur den Naturwissenschaftlichen Grundlagen des Ackerbaus,* Seite 663; Braunschweig, 1883. Hellriegel grew plants in 4 kilograms of clean quartz sand and supplied them with nutrient solutions. The loss by evaporation from uncropped pots was used in determining losses by transpiration. In later experiments covers were used in order to cut down evaporation.

[4] King, F. H., *Physics of Agriculture,* p. 139; published by author, Madison, Wis., 1910. Also, *The Number of Inches of Water Required for a Ton of Dry Matter in Wisconsin;* Wis. Agr. Exp. Sta., 11th Ann. Rep., pp. 240-248, 1894; and *The Importance of the Right Amount and Right Distribution of Water in Crop Production;* Wis. Agr. Exp. Sta.,

2. Climate—Rain, humidity, sunshine, temperature, and wind.

3. Moisture and fertility.[1]

Not only do different plants [2] show a variation of transpiration the same season, but the same plant may give a totally different transpiration in separate years. This is due in part to inherent differences in the plant itself. For example, the extent of leaf surface or root zone would materially influence the transpiration relationship under any given condition. However, a great deal of the variation observed in the ratios already quoted arises from differences in climatic conditions. As a general thing, the greater the rainfall the higher is the humidity and the lower is the relative transpiration. This accounts for the high figures obtained by Widtsoe [3] in Utah. Montgomery [4] found, in studying the water require-

[1] Fertility is used here in the sense of potential productivity. It refers especially to the ultimately available nutrients of the soil.

[2] Miller, E. C., and Coffman, W. B., *Comparative Transpiration of Corn and the Sorghums;* Jour. Agr. Res., Vol. XIII, No. 11, pp. 579-604, June, 1918.

[3] Widtsoe, J. A., *The Production of Dry Matter with Different Quantities of Irrigation Water;* Utah Agr. Exp. Sta., Bul. 116, 1912. Also, *Irrigation Investigations. Factors Influencing Evaporation and Transpiration;* Utah Agr. Exp. Sta., Bul. 105, 1909.

[4] Montgomery, E. G., and Kiesselbach, T. A., *Studies in Water Requirements of Corn;* Nebr. Agr. Exp. Sta., Bul. 128, p. 4, 1912.

14th Ann. Rep., pp. 217-231, 1897. King used cans holding about 400 pounds of soil. Some were set down into the earth while others were not. Part of the work was carried on in the field; the remainder was run in vegetative houses. Normal soils were used. Evaporation from soil was very low, water being added from beneath. The data quoted are the average of a large number of tests.

[5] Leather, J. W., *Water Requirements of Crops in India;* Memoirs, Dept. Agr., India, Chem. Series, Vol. I, No. 8, pp. 133-184, 1910, and No. 10, pp. 205-281, 1911. Jars containing from 12 to 48 kilograms of soil were used. Loss by evaporation was determined on bare pots. The plants were grown in culture houses or in screened inclosures.

[6] Briggs, L. J., and Schantz, H. L., *Relative Water Requirement of Plants;* Jour. Agr. Research, Vol. III, No. 1, pp. 1-63, 1914. Also, *The Water Requirements of Plants;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 284, 1913. Plants were grown in cans holding 250 pounds of soil. Evaporation from soil was prevented by means of a paraffin covering. Work was conducted in screened inclosures. The data are the average of several years' work.

ments of corn under greenhouse conditions, that an increase in the percentage humidity from 42 to 65 lowered the transpiration ratio from 340 to 191. In general, temperature, sunshine, and wind vary together in their effect on transpiration. That is, the more intense the sunshine, the higher is the temperature, the lower is the humidity, and the greater is likely to be the wind velocity. All this would tend to raise the transpiration ratio.

From the soil standpoint, however, the factors inherent in the soil itself are of more vital importance as regards transpiration, since they can be controlled to a certain extent under field conditions. An increase in the moisture content of a soil usually results in an increased transpiration ratio. The work of Hellriegel [1] with barley grown in quartz sand containing a nutrient solution may be cited in this regard, together with the data obtained by Montgomery [2] at Lincoln, Nebraska, with maize grown in a loam soil:

TABLE XXXV

EFFECT OF SOIL-MOISTURE ON TRANSPIRATION.

BARLEY—HELLRIEGEL		MAIZE—MONTGOMERY	
SOIL-MOISTURE PERCENTAGE OF TOTAL CAPACITY	TRANSPIRATION RATIO	SOIL-MOISTURE PERCENTAGE OF TOTAL CAPACITY	TRANSPIRATION RATIO
80	277	100	290
60	240	80	262
40	216	60	239
30	223	45	229
20	168	35	252
10	180		

[1] Hellriegel, H., *Beiträge zu den Naturwissenschaftlichen Grundlage des Ackerbaus,* Seite 629, Braunschweig, 1883.

[2] Montgomery, E. G., *Methods of Determining the Water Requirements of Crops;* Proc. Amer. Soc. Agron., Vol. 3, p. 276, 1911.

These data show clearly that an excessive amount of moisture in the soil is not a favorable condition for the economical use of water.

The amount of available nutrients is also concerned in the economic utilization of water. In general the data along these lines show that the more productive the soil the lower is the transpiration ratio. Therefore, a farmer, in raising the productivity of his soil by drainage, lime, good tillage, green-manures, barnyard manures, and fertilizers, provides at the same time for a greater amount of plant production for every unit of water utilized. The total quantity of water taken from the soil, however, will probably be larger.

The following figures from Montgomery [1] are representative of data available on this phase:

TABLE XXXVI

RELATIVE WATER REQUIREMENT OF MAIZE ON DIFFERENT TYPES OF NEBRASKA SOILS, 1911.

Soil	Dry Weight of Plants in Grams per Pot		Transpiration Ratio	
	Manured	Unmanured	Manured	Unmanured
Poor (15 bushels) . . .	376	113	350	549
Medium (30 bushels)	413	184	341	479
Fertile (50 bushels) .	472	270	346	392

The effects of texture have been investigated by a number of men, the work of von Seelhorst [2] and of Widtsoe [3] being

[1] Montgomery, E. G., *Water Requirements of Corn;* Nebr. Agr. Exp. Sta., 25th Ann. Rep., p. xi, 1912.

See also, Hellriegel, H., *Beiträge zu den Naturwissenschaftlichen Grundlage des Ackerbaus,* Seite 629, Braunschweig, 1883.

[2] Seelhorst, C., von., *Über den Wasserverbrauch von Roggen, Gerste, Weizen, und Kartoffeln;* Jour. f. Landwirtschaft, Band 54, Heft 4, Seite 316-342, 1906.

[3] Widtsoe, J. A., *Irrigation Investigations. Factors Influencing Evaporation and Transportation;* Utah Agr. Exp. Sta., Bul. 105, 1909.

perhaps the most reliable. While these investigators found in general that plants on heavy soils exhibited a low transpiration ratio, hasty conclusions must not be drawn. Since the fine-textured soils contain more nutrient materials, it is probable that this is also a factor.

101. Amounts of water necessary to mature a crop.—Although it may be seen from the transpiration ratios cited that the amount of water necessary to mature the average crop is very large, a concrete example under humid conditions may be cited to advantage. A fair estimate of the dry matter produced in the above-ground parts of a forty-bushel crop of wheat would be about two tons. Assuming the transpiration ratio to be 300, the amount of water actually used by the plant would amount to 600 tons to the acre, or about 5.2 inches of rainfall. This does not include the evaporation that is continually going on from the soil surface, which might very easily amount to as much more. The demand in total, to say nothing of run-off and drainage, is at least equal to 10 inches of rainfall.

102. Rôle of capillarity in supplying the plant with water.—A query arises at this point regarding the mode by which this immense quantity of water is supplied to the plant. The rootlets, especially their absorbing surfaces, are few in number as compared with the interstitial angles that contain most of the water retained in the soil. How, then, does the plant avail itself of water not in immediate contact with its rootlets? This question has been anticipated in the discussion concerning the capillary equilibrium which tends to occur in all soils. As soon as the rootlet begins to absorb at one point the film in that interstitial angle is thinned. A considerable convexity of the water surface occurs at that point, resulting in an inward pull, which causes the water to move in all directions toward that point. Thus a feeding rootlet by absorbing some of the moisture with which it is in contact, creates a condition of instability which results in

considerable film movement. It can, therefore, be said that capillarity is an important factor in any soil in supplying the plant with proper quantities of moisture.

Many of the early investigators have over-estimated the distances through which this adjustment may be effective in properly supplying the plant. It must always be kept clearly in mind that it is the rate of water supply that is the controlling factor. Therefore, capillarity, although it may act through a distance of eight or ten feet if time enough be allowed, may actually be of immediate practical importance through only a few inches as far as the crop is concerned. No extended data are available as to this particular phase, but the knowledge of capillary movement indicates that capillarity of the soil is of greatest importance in a restricted zone immediately around the surface of each absorbing root.[1]

103. Why plants wilt.—As has already been indicated, water may be of little use to a plant because of distance, since capillary action may not move the water rapidly enough for normal needs. Water near at hand may be unavailable through the obstruction of capillarity, friction in this case being the cause. As the rootlet thins the interstitial film at any point, the surface tension equilibrium is disturbed and water moves toward the absorbing surface. This movement is rapid enough for plant needs until the film channels on the particles become thin. As such a condition approaches, friction increases rapidly, cutting down the capillary movement to such an extent as to interfere with the normal functions of the plant.

Wilting occurs, therefore, merely because the soil is unable to move the water rapidly enough for crop needs. As the friction increases very rapidly after the point of lento-capillarity is reached, the wilting coefficient is a figure somewhat

[1] Burr, W. W., *The Storage and Use of Soil Moisture;* Nebr. Agr. Exp. Sta., Res. Bul. 5, 1914.

Miller, E. C., *Comparative Study of the Root System and Leaf Areas of Corn and Sorghums;* Jour. Agr. Res., Vol. VI, No. 9, pp. 311-331, 1916.

less than the percentage representing the lento-capillarity. Since the inner capillary water moves very sluggishly if at all, wilting must occur before the plant has drawn to any great extent on this part of the capillary moisture. The hygroscopic water is, therefore, wholly unavailable to plants and generally some of the capillary as well, although Alway [1] has shown that under certain conditions the plant may reduce the moisture down to the hygroscopic coefficient. The *wilting coefficient* expressed in soil-moisture terms may be located somewhere between the hygroscopic coefficient and the point of lento-capillarity.

104. The wilting coefficient and its determination.—It has been known for many years that the common plants possess different capacities for resisting drought. This has usually been ascribed to one or more of three causes: (1) differences in root extension; (2) differences in ability to become adjusted to a slow intake of water; and (3) differences in the osmotic pull that plants exert on the soil-water. The last two factors argue for different wilting coefficients for crops on the same soil.

The extended work of Briggs and Shantz,[2] however, indicate that the permanent wilting point, expressed as a soil-moisture percentage, is practically the same for all plants. Later Caldwell [3] demonstrated that this relationship of the physical constants of the soil to the wilting point depends on the rate at which the plant loses water, showing that the soil factors are not entirely dominant in this respect.

The conclusions of Briggs and Shantz, nevertheless, seem

[1] Alway, F. J., *Studies on the Relation of the Non-available Water of the Soil to the Hygroscopic Coefficient;* Nebr. Agr. Exp. Sta., Res. Bul. 3, 1913.

[2] Briggs, L. J., and Schantz, H. L. *The Wilting Coefficient for Different Plants and its Indirect Determination,* U. S. Dept. Agr., Bur. Plant Ind., Bul. 230, 1912.

[3] Caldwell, J. S., *The Relation of Environmental Conditions to the Phenomena of Permanent Wilting in Plants;* Physiological Researches, Station N, Baltimore; U. S. Dept. Agr., Vol. 1, No. 1, July, 1913.

more or less accurate for plants growing under humid conditions. If such is the case, it can be accounted for only by the fact that the soil forces in their effect on the wilting point are so powerful as to over-ride any distinguishing characteristics that the plant itself may possess, or at least reduce such influences within the error of actual experimentation. Crops wilt because they cannot get water fast enough, the wilting coefficient in a humid climate being the same for most plants growing on the same soil.

Briggs and Shantz,[1] in their investigations, devised a very satisfactory method for making determinations of the wilting point. Glass tumblers holding about 250 cubic centimeters of soil in an optimum condition were used. The seeds were placed in this soil after which soft paraffin was poured over the surface in order to stop evaporation, thus removing this disturbing factor in the capillary equilibrium of the moisture. The seedlings on germination were able to push through this paraffin. While the plants were developing, the tumblers were kept standing in a constant-temperature vat of water in order to prevent condensation of moisture on the inside of the glass. The vegetative room was under temperature control. When definite wilting occurred, as determined in a saturated atmosphere, a moisture determination was made on the soil. The resulting figure, expressed as percentage of moisture based on dry soil, represents the wilting coefficient for the soil used.[2]

It is evident that the wilting coefficient will be influenced

[1] Briggs, L. J., and Schantz, H. L., *The Wilting Coefficient for Different Plants and its Indirect Determination;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 230, pp. 26-33, 1912.

[2] Bouyoucos classifies the capillary water into two groups, *Free* (the more active), and *Capillary-absorbed* (inner capillary). The distinction is made on the basis of his dilatometer (see foot-note, page 155) results, the portion which freezes at about 0°C being considered the more active. The point so established by his dilatometer gives in a general way the wilting coefficient as defined by Briggs and Shantz.

Bouyoucos, G. J., *A New Classification of the Soil Moisture;* Soil Sci., Vol. XI, No. 1, pp. 33-47, Jan., 1921.

by a number of soil conditions. Important among these is texture, which in itself really represents a group of soil conditions. In general the wilting point is much higher on a fine soil than one of a coarse nature. The following data from Briggs and Shantz [1] is interesting in this regard. The wilting coefficient is shown to lie much nearer the hygroscopic coefficient than to the figure representing the maximum absorption capacity as determined by the Hilgard method.

TABLE XXXVII

RELATION OF THE WILTING COEFFICIENT TO THE TEXTURE OF THE SOIL, THE HYGROSCOPIC COEFFICIENT AND THE CALCULATED MAXIMUM ABSORPTIVE CAPACITY OF THE SOIL FOR WATER.

Soil	Hygroscopic Coefficient	Wilting Point	Calculated Maximum Absorption Capacity
Coarse sand.....	.5	.9	25.7
Fine sand.....	1.5	2.6	28.5
Fine sand.....	2.3	3.3	30.5
Sandy loam.....	3.5	4.8	34.9
Sandy loam.....	4.4	6.3	39.2
Fine sandy loam ..	6.5	9.7	49.1
Loam.....	7.8	10.3	50.8
Loam.....	9.8	13.9	61.3
Clay loam.....	11.4	16.3	68.2

In studying the correlation of this wilting coefficient to soil conditions Briggs and Shantz [2] advanced the following relationships. Expressed as formulæ, they represent methods

[1] Briggs, L. J., and Schantz, H. L., *The Wilting Coefficient for Different Plants and its Indirect Determination;* U. S. Dept. Agr., Bur. Plant Ind., Bul 230, p. 65, 1912.

See also Heinrich, R., *Über das Vermögen der Pflanzen den Bodenen Wasser zu erschöpfen;* Jahresbericht der Agr.-chem., Band 18, Seite 368-372, 1875.

[2] Briggs, L. J., and Shantz, H. L., *The Wilting Coefficient for Dif-*

of at least approximating the wilting point from other soil factors. These formulæ [1] are arranged in the order of their reliability, based on the data obtained by the authors:

$$1.\ \text{Wilting coefficient} = \frac{\text{Moisture equivalent}}{1.84}$$

$$2.\ \text{Wilting coefficient} = \frac{\text{Hygroscopic coefficient}}{.68}$$

$$3.\ \text{Wilting coefficient} = \frac{\text{Water-holding capacity (Hilgard Method)} - 21}{2.9}$$

While such formulæ are only approximate in their application, they are valuable for rough calculations. They also show in a general way the correlations between the various moisture conditions established by experimental methods.

105. The availability of the soil-water.—From the discussions already presented regarding the forms of water in the soil, the ways in which they are held, and their movements, it is evident that all moisture present in a soil is not available for plant growth. Three divisions of the soil-water may be made on this basis: *unavailable, available,* and *superfluous.*

It is obvious that all of the moisture below the wilting point is out of reach of the plant and may be classified as unavailable. It includes all of the hygroscopic and that part of the capillary which is tightly held, the so-called inner capillary water. The amount of the capillary moisture unavailable to plants is much greater with clayey than with sandy soils. For example, a sand with a hygroscopic coefficient of 1.5 per cent.

ferent Plants and its Indirect Determination; U. S. Dept. Agr., Bur. Plant Ind., Bul. 230, pp. 56-77, 1912.

See also, Loughridge, R. H., *Investigations in Soil Physics;* Calif. Agr. Exp. Sta., Rep. 1892-3-4, pp. 70-100, 1894. Alway, F. J., and Clarke, V. L., *Use of Two Indirect Methods for the Determination of the Hygroscopic Coefficient of Soils;* Jour. Agr. Res., Vol. VII, No. 8, pp. 345-359, Nov., 1916.

[1] Note that the wilting coefficient, moisture equivalent, water-holding capacity and hygroscopic coefficient are expressed in percentage of water based on dry soil.

and a wilting coefficient of 2.6 per cent. has 1.1 per cent. of water of a capillary nature unavailable. A clay loam having a hygroscopic coefficient of 11.4 per cent. and a wilting coefficient of 16.3 per cent. would contain 4.9 per cent. of capillary water unavailable to crops. It must be remembered, however, that under certain conditions plants may reduce the capillary moisture almost to the hygroscopic coefficient.[1] The moisture so obtained is probably not utilized for growth activities.

Advancing from the wilting, or critical, moisture content of a soil, all the remaining capillary water is found to be avail-

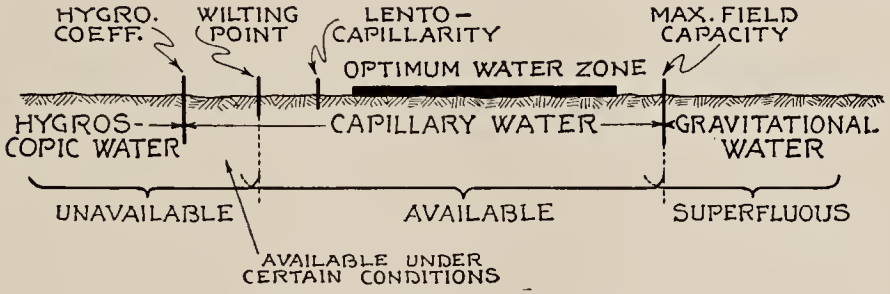


FIG. 35.—Diagram showing the various forms of water that may be present in the soil and their relations to higher plants.

able for normal plant use. However, when free water begins to appear, a condition detrimental to growth is established, conditions becoming more adverse as the saturation point is approached. This free water is designated as the superfluous water and its presence generates conditions unfavorable to plants. The bad effects of free water on the plant arise largely from the poor aëration that results from its presence.[2] Not only are the roots deprived of their oxygen, but toxic materials tend to accumulate. Favorable bacterial activities, such as the production of ammonia and nitrates, are much re-

[1] Alway, F. J., *Studies on the Relation of the Non-available Water of the Soil to the Hygroscopic Coefficient;* Nebr. Agr. Exp. Sta., Res. Bul. 3, 1913.

[2] It must be kept in mind that in a clayey soil the superfluous water may include some of the upper capillary moisture.

tarded also. The various forms of water in the soil and their availability to the plant are illustrated diagrammatically in Fig. 35, page 199.

This diagram may be evaluated in a general way as below, using the sandy and clayey soils for which full physical data have already been given in Chapter VIII. (See footnote on page 179.)

TABLE XXXVIII

THE EVALUATION OF FIG. 35 FOR A SANDY AND CLAYEY SOIL, RESPECTIVELY.

	SANDY SOIL	CLAYEY SOIL
Hygroscopic coefficient	1.00	10.00
Wilting point	1.47	14.70
Maximum field capacity	17.00	44.00
Unavailable water	1.47	14.70
Available water	15.53	29.30
Superfluous water	8.00	1.60

106. Optimum moisture for plant growth.—It is very evident that there must be some moisture condition of a soil which is best for plant development. This is usually designated as the optimum content. It is not to be assumed, however, that the total range of the available soil-water represents this condition. Nor is this optimum water content in any particular soil to be designated by a definite percentage. In reality the moisture in a soil may undergo considerable fluctuation and yet allow the plant to develop normally.[1] This is because the physical condition of the soil changes with varying water content and the plant is able to accommodate

[1] Wollny, E., *Untersuchung über den Einfluss der Wachsthumsfaktoren auf des Produktionsvermögen der Kulturpflanzen;* Forsch. a. d. Gebiete d. Agri.-Physik., Band 20, Seite 53-109, 1897.

Mayer, A., *Über den Einfluss kleinerer oder grosserer Mangen von Wasser auf die Entwickelung einiger Kulturpflanzen;* Jour. f. Landw., Band 46, Seite 167-184, 1898.

itself to such a fluctuation without a disturbance in its normal development. Granulation has considerable influence on the range of optimum moisture conditions, since the better the granulation, the better able is the soil to accommodate itself to changes in water content without a disturbance of normal growth. In moisture conservation and control, a granular soil is one of the first improvements to be aimed at. Drainage, liming, addition of organic matter, and tillage, by leading up to such a condition, increase the effectiveness and economy of soil moisture utilization.

Many of the ordinary farming operations have to do with the maintenance of an optimum moisture condition in the soil. During periods of excessive rainfall, especially during the growing season, conditions should be such as to allow the presence of free water in the soil for the briefest time possible. This means adequate under-drainage and satisfactory arrangements whereby the run-off may be removed with but little damage. Moisture control also demands conservation methods of more or less intensity in arid and semi-arid regions supplemented by irrigation, whereby the soil-moisture may never drop much below the point of lento-capillarity. By such arrangments the optimum moisture conditions, so essential to normal and uninterrupted crop growth, are maintained.

CHAPTER X

THE CONTROL OF SOIL-MOISTURE

In the discussion of the water requirements of plants it was apparent that for a normal yield of any crop, the amount used by the plant alone was very great, varying from five to ten acre-inches according to conditions. Were this the only loss of water, the question of raising crops with given amounts of rainfall would be a simple one. Three further sources of water loss, however, are usually operating in the soil and tending to lower the water that would go toward transpiration, a loss absolutely necessary for proper growth. The various ways by which water finds an exit from a soil are: (1) transpiration, (2) run-off over the surface, (3) percolation, and (4) evaporation. The diagram (Fig. 36) makes clear their relationships.

It is immediately obvious that, as the losses by run-off, leaching, and evaporation increase, the amount of water left for crop utilization decreases. Some control of soil-water is, therefore, necessary both in an arid and a humid region. Under arid and semi-arid conditions, where run-off and percolation are not of such great importance except where irrigation is practiced, loss by evaporation is of especial consequence, as it competes directly with the plant. Under humid conditions, losses by percolation and run-off seem to merit the greater attention, because of the loss of nutrients with the former and the erosion damage from the latter. The influence of evaporation, however, is not to be under-estimated or neglected. Control of moisture is, therefore, necessary in all regions. This control consists in so adjusting run-off, leach-

ing, and evaporation as to maintain optimum moisture conditions in the soil at all times. Such control should result in a proper and economical utilization of soil-water by the plant.

107. Run-off losses.—In regions of heavy rainfall or in areas where the land is sloping or rather impervious to water, a considerable amount of moisture received as rain is likely to be lost by running away over the surface. Under

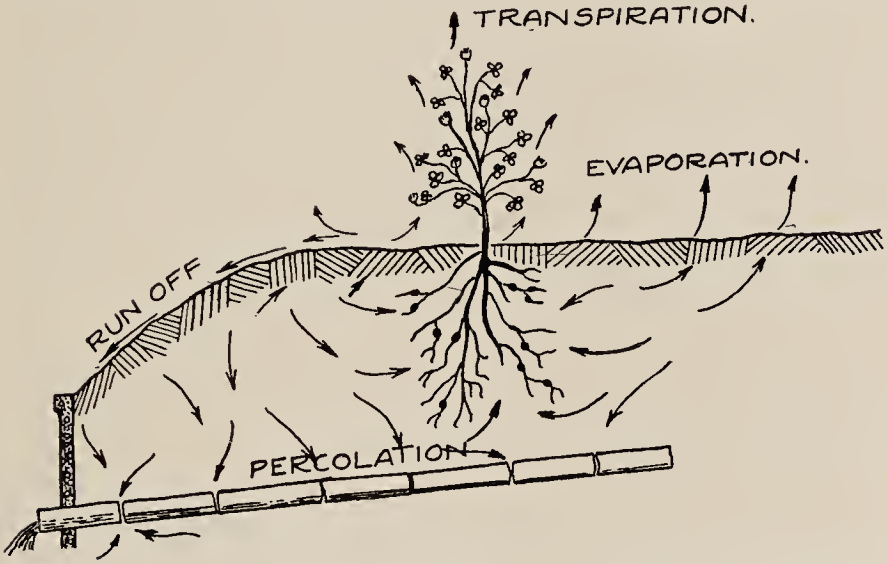


FIG. 36.—Diagram illustrating the various ways by which water may be lost from a soil.

such conditions two considerations are important: (1) the loss of water that might otherwise be of use to plants; and (2) the erosion that usually occurs when much water escapes in this manner. Of the two, the latter is generally the more important. The amount of run-off varies with the rainfall and its distribution, the slope, the character of the soil, and the vegetative covering. In some regions loss by run-off may rise as high as 50 per cent. of the rainfall, while in arid sections it is of course very low, unless the rainfall is of the torrential type as in the arid Southwest.

The quantity of water entering a soil is determined almost entirely by the physical condition of the soil. If it is loose and open, the water enters readily and little is lost over the surface as run-off. If, on the other hand, the soil is compact, impervious and hard, most of the rainfall runs away, and not only is there a serious loss of water, but considerable erosion may also result. The first step in checking run-off losses, therefore, is strictly physical in nature. Good tillage and plenty of organic matter by encouraging granulation have much to do with the proper entrance of water into the soil as well as with its economic utilization therein.

108. Erosion by water and its control.[1]—While every one is familiar with the importance of water in the formation of alluvial and marine soils, the concurrent destructive action that is going on in the uplands is generally overlooked. This is due to the fact that erosion is often considered as more or less uncontrollable, an ill that can not be avoided. In Wisconsin, for example, 50 per cent. of the tillable land is subject to erosion of economic importance.[2] Even in as level a state as Illinois, 17 per cent. of the area is detrimentally eroded.[3] The waste by erosion is as great in other states, even those of an arid climate. Davis [4] has estimated that 870 million tons of suspended material are carried each year into the ocean by the streams of the United States. Since this is only a very small fraction of the soil brought down from the

[1] Davis, R. O. E., *Economic Waste from Soil Erosion;* U. S. Dept. Agr., Year Book for 1913, pp. 207-220.
Ramser, C. E., *Terracing Farm Lands;* U. S. Dept. Agr., Farmers' Bul. 997, 1918.
Eastman, E. E., and Glass, J. S., *Soil Erosion in Iowa;* Ia. Agr. Exp. Sta., Bul. 183, Jan., 1919.
Fisher, M. L., *The Washed Lands of Indiana;* Ind. Agr. Exp. Sta., Circ. 90, Feb., 1919.

[2] Whitson, A. R., and Dunnewald, T. J., *Keep Our Hillsides from Washing;* Wis. Agr. Exp. Sta., Bul. 272, Aug., 1916.

[3] Mosier, J. G., and Gustafson, A. F., *Soil Physics and Management,* p. 358, Philadelphia, 1917.

[4] Davis, R. O. E., *Economic Waste from Soil Erosion;* U. S. Dept. Agr., Year Book for 1913, p. 213.

uplands by running water, erosion is no insignificant factor in soil management considerations.

Two types of erosion are generally recognized, sheet and gully. In the former, soil is removed more or less uniformly from every part of the slope. Gullying occurs where the volume of water is concentrated, resulting in the formation of ravines by undermining and downward cutting. Both types of erosion are serious.

A number of different methods for the effective prevention and control of erosion may be utilized. Anything that will increase the absorptive capacity of the soil, such as deep plowing, surface tillage, and increase of organic matter, will lessen the run-off over the surface. On steep slopes, however, such influence is of little importance, since during heavy rainfall absorption is too slow to lessen materially the surface losses. In cultivating corn and similar crops, it is important that the last cultivation be across the slope rather than with it. On long slopes subject to erosion, the fields may be laid out in long narrow strips across the incline, alternating the tilled crops, such as corn and potatoes, with hay and grain. The grassed areas tend to check the surface flow of water. Where the slopes are subject to very serious erosion, they should either be reforested or kept in permanent pasture, guarding always against incipient gullying.

About the only effective means of controlling sheet erosion is by terracing of some kind. Strong prejudice exists in many communities against terraces, since they usually waste land, are often unsightly and are a serious obstacle to harvesting machinery. The Mangum terrace [1] however, is worthy of especial attention, since it obviates the really serious objections to the ordinary terrace while maintaining the desired water control. The Mangum terrace is generally a broad bank of earth with gently sloping sides, contouring the field at a

[1] First constructed by P. H. Mangum of Wake County, North Carolina.

grade from 10 to 12 inches to the 100 feet. It is usually formed by back-furrowing and scraping. The interval between the embankment depends on the slope. Since the terrace is low and broad, it may be cropped without difficulty and offers no obstacle to cultivating and harvesting machinery. It wastes no land, and eliminates breeding places for insects.

Small gullies, while at first insignificant, soon enlarge into deep unsightly ravines. While they may be plowed-in or otherwise filled up, such a procedure is generally a waste of time, since the gullies form again with the next heavy wash. A number of different methods are in use for the control of gullying, depending on conditions. Staking is a very common procedure, the size of the stakes increasing with the magnitude of the gully. The stakes are usually interwoven with brush, although stone, straw, and other material may be utilized. If brush or other loose material is used, it should be staked to the ground or held down by stone or dirt. Otherwise, the water will run beneath the fill and no benefit will result. Dams of earth, concrete, or stone are often installed with success. They must be supplemented by a tile-drain outlet, however, with an elbow just above the dam. The dam checks the water until it rises to the level of the elbow outlet and is then carried away through the tile. Most of the sediment is deposited above the dam and the gully is slowly filled.

109. Percolation losses and their control.—When at any time the amount of rainfall entering a soil becomes greater than its water-holding capacity, losses by percolation will result. The losses will depend largely on the amount and distribution of the rainfall and the capability of the soil to hold moisture. The objectionable features of excessive percolation are two: (1) the actual loss of water, and (2) the leaching-out of salts that may function as nutrients to plants.

The results from the Rothamsted lysimeter [1] from 1871-

[1] Hall, A. D., *The Book of the Rothamsted Experiments*, p. 22, New York, 1917.

1913 on a bare clay loam three feet deep are interesting as to the light they afford regarding actual drainage losses in humid regions:

TABLE XXXIX

PERCOLATION THROUGH A SIXTY-INCH COLUMN OF BARE CLAY LOAM. ROTHAMSTED EXPERIMENT STATION, ANNUAL AVERAGE OF 42 YEARS.

PERIODS	RAINFALL INCHES	DRAINAGE INCHES	PERCENTAGE OF RAINFALL AS DRAINAGE
Dec.-Feb.	6.77	5.58	82.4
Mar.-May	5.96	2.11	35.4
June-Aug.	7.83	1.82	23.2
Sept.-Nov.	8.29	4.50	54.2
Mean Total	28.85	14.01	48.8

It appears from these figures that the drainage loss is much lower in summer than winter, the ratio being about one to three. It is also to be noted that about 50 per cent. of the rainfall in such a climate as England is lost by percolation through a bare soil. This compares fairly well with Wollny's [1] summary on eighteen soils in England, Switzerland, and Germany. These soils, most of which were bare, showed a loss of over 41 per cent. of the rainfall by drainage.

Recent results,[2] due to variable conditions, are by no means in agreement, ranging from a low to a very high percentage loss of the rainfall. It seems fair to assume, however, that, as soils are handled in humid regions, over half of the rainfall is lost by percolation and run-off combined.

Percolation seems to be influenced, not only by the amount

[1] Wollny, E., *Untersuchungen über die Sickerwassermengen in verschiedenen Bodenarten;* Forsch. a. d. Gebiete d. Agri.-Physik., Band 11, Seite 1-68, 1888.

[2] For excellent review of literature see Lyon, T. L., and Bizzell, J. A., *Lysimeter Experiments;* Cornell Agr. Exp. Sta., Memoir 12, June, 1918.

of rainfall and its distribution, but also by evaporation, the character of the soil, and the presence of a crop. As the rainfall increases, percolation increases, being much greater in New York, for example, than in Utah. Evaporation has a marked influence, reducing drainage losses to a considerable degree. The drainage through sandy soils is generally larger than through clayey soils under strictly humid conditions and where run-off is a factor. When evaporation is high, sandy soils have been known to percolate very much less than those of a heavier nature.[1] Field crops, in that they utilize a large amount of moisture, have always been found to reduce percolation losses.

The loss of moisture by percolation is the least objectionable feature of the phenomenon, since it is often necessary, especially during the spring and summer, to rid the soil very quickly of superfluous water. The loss of nutrient salts is more vital, since the materials so carried away might be used by plants. The loss of nitrogen, calcium, and potassium from a bare clay loam at Cornell University [1] over a period of ten years averaged, respectively, 69, 398, and 72 pounds an acre annually. This is equivalent to an acre loss of 419 pounds of sodium nitrate, 995 pounds of calcium carbonate and 137 pounds of potassium chloride every year, which is a larger amount of nutrient material than is removed by an average crop.

Control of percolation is exerted, not so much to save water, as to conserve nutrients. As water enters a soil it moves downward and is continually changing into the capillary state. If the absorptive capacity of the soil is high, little of the rainfall may appear as drainage. The presence of organic matter and the influence of good tillage will do much toward checking drainage losses. Once the absorptive capacity of the soil

[1] Fraps, G. S., *Losses of Moisture and Plant Food by Percolation;* Tex. Agr. Exp. Sta., Bul. 171, 1914.

[2] Unpublished data. Cornell Agr. Exp. Sta., Ithaca, N. Y.

is reached, however, the drainage should be as rapid and complete as possible in order to insure good sanitation. The maintenance of a high absorptive capacity for available water and the facilitation of rapid drainage are the secrets of rational percolation control.

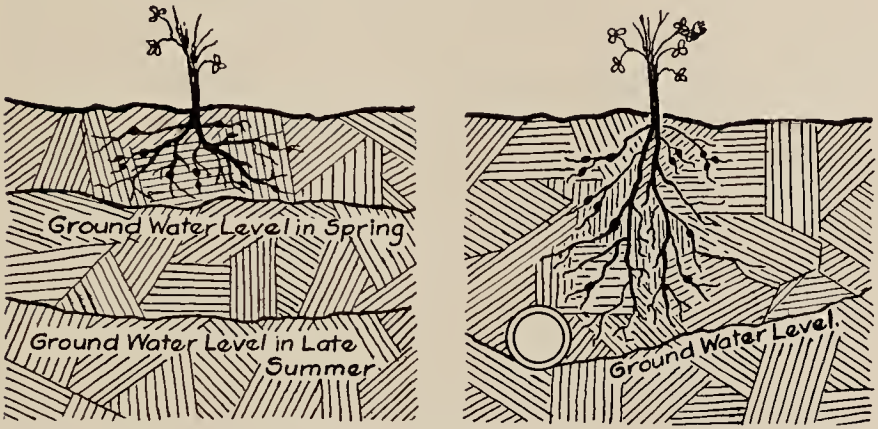


FIG. 37.—Influence of drainage on the ground water and the extent of the root zone.

In this connection it is well to remember that drainage losses are profoundly affected by cropping. The following data from the Cornell Experiment Station are especially interesting in this regard. The data for the Dunkirk and Volusia soils are for ten and five years respectively:

TABLE XL

AVERAGE ANNUAL LOSS OF WATER BY PERCOLATION FROM BARE AND CROPPED SOILS. CORNELL LYSIMETER TANKS.

CONDITIONS	RAINFALL INCHES	PERCOLATION INCHES	RAINFALL AS PERCENTAGE OF DRAINAGE
Dunkirk clay loam:			
Bare	32.41	24.92	76.8
Cropped	32.41	18.70	57.7
Volusia silt loam:			
Bare	32.97	27.13	82.3
Cropped	32.97	20.62	62.5

TABLE XLI

AVERAGE ANNUAL LOSS OF NUTRIENTS BY PERCOLATION FROM BARE AND CROPPED SOILS. CORNELL LYSIMETER TANKS.

CONDITIONS	ANNUAL LOSS IN POUNDS AN ACRE		
	NITROGEN	CALCIUM	POTASSIUM
Dunkirk clay loam:			
Bare	69.0	397.9	72.0
Rotation	7.3	247.1	57.3
Grass	2.5	259.9	61.7
Volusia silt loam:			
Bare	51.8	356.4	84.5
Cropped	10.2	341.4	73.2

The influence of the crop on percolation is obvious, the loss of water by drainage being markedly decreased. The saving of nutrient is also very marked, especially as regards the nitrogen. The loss of nitrogen is only about one-seventh as much from the soils under a rotation, as where the land was bare, while the saving of calcium and potassium is considerable. The importance of catch- and cover-crops in economical soil management need not be emphasized further.

110. Drainage.[1]—While percolation, especially in humid regions, causes the loss of a large proportion of the rainfall received and carries away in addition many tons of

[1] Klippart, J. H., *Principles and Practice of Land Drainage;* Cincinnati, 1894.

Miles, M., *Land Drainage;* New York, 1897.

Faure, L., *Drainage et Assainissement Agricole des Terres;* Paris, 1903.

Elliott, C. G., *Drainage of Farm Lands;* U. S. Dept. Agr., Farmers' Bul. 187, 1904.

King, F. H., *Irrigation and Drainage,* Revised Edition; Part II, New York, 1909.

Warren, G. M., *Tidal Marshes and their Reclamation;* U. S. Dept. Agr., Office Exp. Sta., Bul. 240, 1911.

Woodward, S. M., *Land Drainage by Means of Pumps;* U. S. Dept. Agr., Office Exp. Sta., Bul. 243, 1911.

Elliott, C. G., *Engineering for Land Drainage;* New York, 1912.

Parsons, J. L., *Land Drainage;* Chicago, 1915.

soluble material, it is generally wise to facilitate the rapidity of its action while checking, if possible, its magnitude. The encouragement of the rate of percolate is spoken of as land drainage, which is the process of removing the excess or superfluous water from the soil as rapidly as possible. Excess water, by interfering with aëration, sets up unsanitary conditions within the soil. By draining the land many favorable reactions are promoted. Granulation is encouraged, heaving is checked, while the root zone and water capacity of the soil are markedly increased. By facilitating aëration, favorable chemical and biological changes are encouraged, thus increasing the nutrients available for plants. The sum-total of good drainage is an increase of crop production to such an extent as to meet the investment costs and pay a handsome profit besides.

While the drainage of swamps and the reclamation of overflow areas are urgent, the drainage of lands already under crop is more important. Practical farm drainage is paramount in almost every community, even in arid regions where irrigation must be practiced. Two types of drainage are feasible—open and closed. Ditch drainage is the usual type of the first group. Ditches have the advantage of large capacity and are able to carry water at a low grade. On the other hand, they waste land, are ineffective and inconvenient, encourage erosion and demand a yearly up-keep expenditure. Wherever possible under-drains should be used.

Jeffery, J. A., *Text-Book of Land Drainage;* New York, 1916.

Fippin, E. O., *Drainage in New York;* Cornell Agr. Exp. Sta., Bul. 254, 1908.

Brown, C. F., *Farm Drainage;* Utah Agr. Exp. Sta., Bul. 123, 1913.

Lynde, H. M., *Farm Drainage in North Carolina;* N. C. Agr. Exp. Sta., Bul. 234, 1915.

Yarnell, D. L., *Trenching Machinery Used for the Construction of Trenches for Tile Drains;* U. S. Dept. Agr., Farmers' Bul. 698, 1915.

Leidigh, A. H., and Gee, E. C., *Tile Drainage;* Tex. Agr. Exp. Sta., Bul. 188, 1916.

Hart, R. A., *The Drainage of Irrigated Farms;* U. S. Dept. Agr., Farmers' Bul. 805, 1917.

111. Tile drains are the only reliable means of underdrainage under all conditions. While stone drains[1] are of value in certain cases, they must always be short and are likely to clog. Besides, their drainage is slow and inefficient. On silty soil they do not long remain in service. The operation of the tile drain is simple. The tile, generally about twelve inches long with a diameter varying with the water to be carried, are laid end to end in strings, on the bottom of a trench of sufficient slope, a carefully protected outlet being provided. The tile are then covered with earth, straw or surface soil often being placed directly around the tile to facilitate the entrance of the water. The superfluous water enters the tile through the joints, mostly from the sides. As a consequence, the tops of the joints may be covered with paper, cloth or even cemented in order to prevent the entrance of silt or quick-sand. The function of a tile drain system is twofold: (1) to collect the superfluous water and (2) to discharge it quickly from the land.

Where the land possesses considerable natural drainage, the tile are laid along the depressions. This is spoken of as the *natural* system of drainage in that the tile facilitate the quick removal of the water from the places of natural accumulation. Where the land is level or gently rolling, it often needs uniform drainage. A regular system must then be installed. This may be either of the *fishbone* or *gridiron* style, or a modification or combination of the two, natural drainage being taken advantage of where possible. Where springs or seepage spots occur, cut-off systems must be devised. (See Figs. 38 and 39.)

[1] Stone drains are built by arranging stone in a properly located and graded trench in such a manner as to provide a continuous channel or throat from the upper end of the drain to the lower. One of the safest modes of construction from the standpoint of clogging is to place flat stone on edge in the trench with their faces parallel to the walls of the ditch. The spaces between the stone provide for the movement of the drainage water.

Every regular system consists of two parts, the laterals and the main drain. The laterals are usually constructed of three 3- or 4-inch tile, seldom smaller. These laterals should always enter the main at an angle of about 45 degrees. This causes a joining of the currents with no loss of impetus and

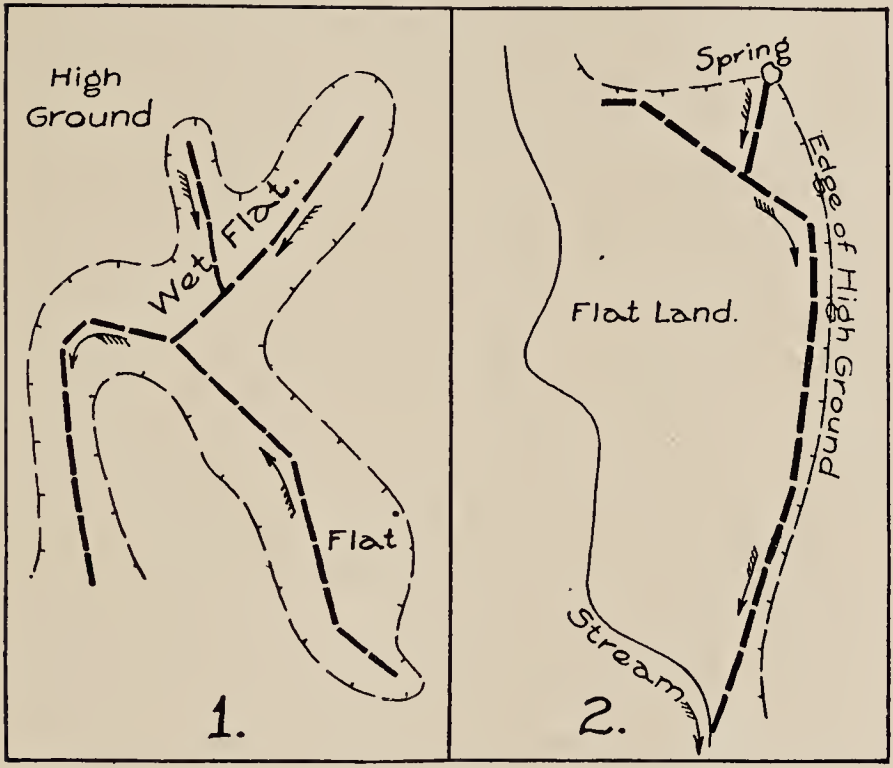


FIG. 38.—Natural (1) and interception (2) systems for laying tile drains.

allows the more rapidly moving lateral streams to speed up the flow in the main drain. The size of the main depends on the rainfall, the area drained, and the slope. It, of course, must be larger near the outlet than at any other point. The following practical table from Elliott [1] indicates the influence

[1] Elliott, C. G., *Engineering for Land Drainage;* p. 108, New York, 1912.

of area and slope on the size of the main near the outlet of any system:

TABLE XLII

GRADES TO A HUNDRED FEET IN DECIMALS OF A FOOT WITH APPROXIMATE EQUIVALENTS IN INCHES.

Diameter of Tile (in Inches)	Grades to a Hundred Feet in Decimals of a Foot with Approximate Equivalents in Inches					
	½ inch	1 inch	2 inches	3 inches	6 inches	9 inches
	0.04	0.08	0.16	0.25	0.50	0.75
	Acres	Acres	Acres	Acres	Acres	Acres
5	17.3	19.1	22.1	25.1	32.0	37.7
6	27.3	29.9	34.8	39.6	50.5	59.4
7	39.9	44.1	51.1	58.0	74.5	87.1
8	55.7	61.4	71.2	80.9	103.3	121.4
9	74.7	82.2	95.3	108.4	138.1	162.6
10	96.9	106.7	123.9	140.6	179.2	211.1
12	152.2	167.7	194.6	221.1	281.8	331.8

The grade necessary for the satisfactory operation of a tile drain system varies with the system itself and the portion under consideration. The grade of the main drain may be very low, especially if the laterals deliver their water with a high velocity. In general, the grade will vary from 4 to 20 inches to the hundred feet, 8 inches being more or less ideal. The depth of the tiles beneath the surface and the distance between laterals will vary with the soil. With sandy soils the tile may be placed as deep as 3 or 4 feet. With clayey soils the depth must be shallower, ranging from 15 to 30 inches, while the interval is reduced as the soil becomes finer in texture. On a clayey soil the distance between the strings is sometimes as low as 35 feet although 50 to 70 feet is commoner.

The maintenance cost of a tile drain system is low, the only especial attention needful being at the outlet. The outlet

should be well protected, so that the end tiles may not be loosened and the whole system endangered by clogging with sediment. It is well to embed the end tile in a masonry or concrete wall. The last eight or ten feet of tile may even be replaced by a galvanized iron pipe or with sewer tile, thus

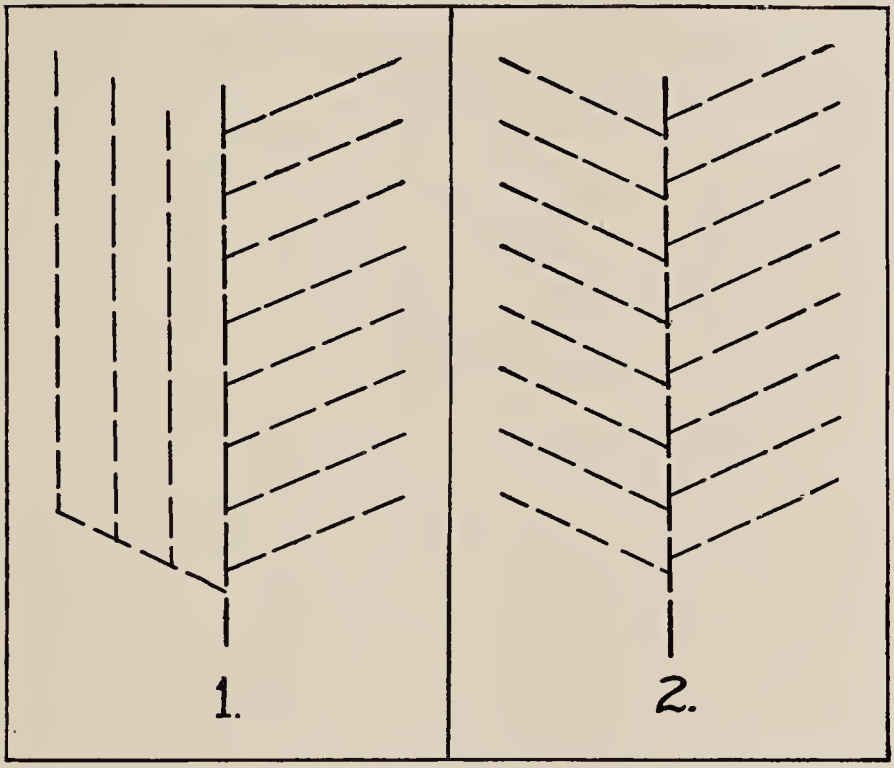


FIG. 39.—Gridiron and fishbone systems for laying tile drains.

insuring against damage by frost. The water should flow freely from a tile drain system, as a drowned outlet interferes with efficient drainage. The opening of a tile drain system is usually protected by a gate or by wire in such a manner as to allow the water to flow out freely but preventing rodents from entering in dry weather. (See Fig. 40.)

As with any other improvement, tile drainage must be made

to pay. If rapid efficient drainage can not be assured at a reasonable cost and under such conditions that the increased crops will return a good profit on the investment, tile drains should not be installed.

112. Evaporation losses.—Evaporation of soil-water takes place almost entirely at the surface, exceptions being where large cracks occur, which allow thermal loss directly from the subsoil. This loss of water by direct evaporation from the soil may be excessive and may result in direct reduc-

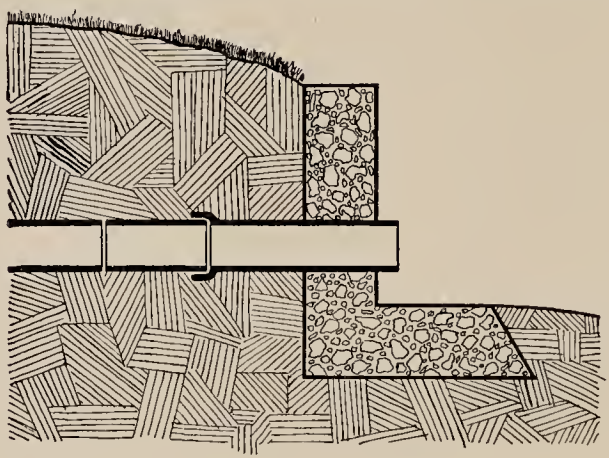


FIG. 40.—Cement block at the outlet of a tile drain.

tion of crop yield, a type of loss so familiar that examples hardly need be cited. In the results with the Rothamsted rain gauges (see page 207), about 50 per cent. of the annual rainfall was regained in the drainage water. Since the gauges bore no crop, the remaining 50 per cent. must have been lost by evaporation. It should be noted that in the summer months under warm temperature, this loss was greatest, amounting to 75 per cent. of the rainfall. Correspondingly, in the semi-arid and arid sections of the country where there is little or no drainage, the rainfall is almost all lost by evaporation. Evaporation from land surface has an appreciable effect on

the amount of rainfall. Even in humid regions, where the annual rainfall is ample for maximum crop production, the yields are frequently reduced below the profit point by prolonged periods of dry weather in the growing season during which the loss of water from the plants, coupled with the loss from the soil and through weeds, exhausts the moisture supply very rapidly.

While run-off and percolation are directly proportional to the rainfall, loss by evaporation does not vary to such a degree. The loss by percolation depends almost directly on the amount of rainfall above the retentive power of the soil. In years of heavy precipitation losses by percolation increase. Evaporation from the soil depends largely on the length of time that the soil surface is moist, and this will not vary markedly from year to year. The following figures from the Rothamsted [1] sixty-inch drain gauge may be quoted in this regard:

TABLE XLIII

RAINFALL, DRAINAGE AND EVAPORATION AT THE ROTHAMSTED EXPERIMENT STATION, 1871 TO 1912.

CONDITIONS	RAINFALL INCHES	PERCOLATION INCHES	EVAPORATION INCHES
Maximum rainfall, 1903....	38.69	24.23	14.46
Mean total for 42 years....	28.75	13.93	15.32
Minimum rainfall, 1898....	20.49	7.69	12.80

A rough calculation may be made which will show the apportionment of the yearly rainfall in a humid region of the temperate zone between the four forms of losses—run-off and percolation, evaporation, and transpiration. The percolation under a rainfall, say, of 28 inches, as shown by the Rotham-

[1] Hall, A. D., *The Book of the Rothamsted Experiments;* p. 22, New York, 1917.

sted work, is roughly 14 inches. Run-off and percolation may be considered as about 50 per cent. The water requirement of an ordinary crop is about 7 inches. This leaves a loss of 7 inches to be credited to evaporation. In other words, in a clay loam soil in a climate like that of England, one-half the rainfall goes as run-off and percolation, while the other half is divided about equally between the plant and loss by evaporation. While run-off and percolation may be checked to some extent, not enough conservation can occur in this direction to tide a crop over a period of drought. Some consideration should, therefore, be directed towards the checking of loss by evaporation, since moisture thus saved means just that amount added to the water available for the use of the crop growing on the soil.

113. Evaporation control.—Any material applied to the surface of a soil primarily to prevent loss by evaporation or to keep down weeds may be designated as a mulch. Mulches are of two general sorts, artificial and natural. In the former case, foreign material is merely spread over the soil surface. Manure, straw, leaves, and the like may be used successfully. Such mulches while effective, especially in preventing weed growth, are not generally applicable to field crops where inter-tillage is practiced, since they would make cultivation impossible. Their use is, therefore, limited to such crops as strawberries, blackberries, and the like.

The second type of mulch is called a soil-mulch since it is formed from soil itself. With proper tillage, a loose dry layer of soil may be formed on the surface. Such a layer is designed to obstruct capillary movement to such an extent as to reduce evaporation loss to a minimum. In theory a soil-mulch should be formed as quickly as possible so that the only moisture sacrificed will be that which is present in the soil forming the mulch. Moreover, the mulch should be renewed after every rain and should, except in special cases, be not more

than three inches deep. Late in the season, especially for corn, the cultivation should be shallow to prevent root-pruning.[1]

For many years cultivation for a soil-mulch has been advocated for two reasons: (1) checking of evaporation, and (2) the killing of weeds. Either procedure, if successful, will allow the crop a larger proportion of the rainfall. Recent experimental results, however, seem to indicate that a soil-mulch with an intertilled crop does not check evaporation compared with a soil uncultivated and kept free of weeds. This is probably due to the fact, that even with moisture a limiting factor, the water sacrificed in renewing the mulch is not offset by that conserved. The tendency of soils, especially those of a sandy character to self-mulch as well as the action of the roots of the crop in intercepting the water, may also be factors. Under greenhouse conditions and in regions of very little rainfall, the soil-mulch probably does conserve

[1] Since a great many of the inter-tilled crops are shallow-rooted, great care should be exercised in cultivation, especially toward the latter part of the growing season. Corn and potatoes are especially influenced by root-pruning. The following data[2] averaged for 7 years are pertinent:

INFLUENCE OF ROOT-PRUNING ON THE YIELD OF CORN IN BUSHELS TO THE ACRE. AVERAGE OF 7 YEARS. UNIVERSITY OF ILLINOIS

TREATMENT	YIELD
No cultivation, weeds kept down with hoe	67.7
Shallow cultivation	70.8
Deep cultivation	68.6
Shallow cultivation, roots unpruned	74.8
Shallow cultivation, roots pruned with knife	61.6
Surface scraped, roots unpruned	80.7
Surface scraped, roots pruned with knife	68.3

[2] Mosier, J. G., and Gustafson, A. F., *Soil Moisture and Tillage for Corn;* Ill. Agr. Exp. Sta., Bul. 181, 1915.

moisture. The following figures[1] are representative of the data available regarding these points:

TABLE XLIV

MOISTURE CONTENT OF BARE IRRIGATED AND DRY-LAND PLOTS, TREATED IN VARIOUS WAYS, EXPRESSED IN TOTAL INCHES OF WATER IN UPPER 6 FEET OF SOIL. GARDEN CITY, KANSAS, 1914.

Treatment	Irrigated			Dry Land		
	Mar. 30	Sept. 16	Gain or loss	Mar. 30	Sept. 16	Gain or loss
6-inch mulch....	17.6	15.9	—1.7	11.8	12.4	+ .6
3-inch mulch.....	18.1	16.6	—1.5	11.3	11.7	+ .4
Bare surface.....	17.8	15.6	—2.2	11.5	12.0	+ .5
Weeds.....	16.4	9.1	—7.3	10.8	8.0	—2.8

TABLE XLV

EFFECTS OF VARIOUS METHODS OF TILLAGE ON THE YIELD OF CORN AND THE AVERAGE PERCENTAGE OF MOISTURE IN THE SOIL TO A DEPTH OF 40 INCHES. AVERAGE OF 8 YEARS' TEST AT THE UNIVERSITY OF ILLINOIS.[2] MEAN RAINFALL, 33.7 INCHES.

Treatment	Yield of Corn Bushels Per Acre	Average Percentage of Moisture in Soil
Not plowed or cultivated:		
Kept bare of weeds only....	31.4	23.1
Plowed and seedbed prepared:		
Kept bare of weeds only.....	45.9	22.3
Weeds allowed to grow.....	7.3	21.8
Three shallow cultivations....	39.2	21.9

[1] Call, L. E., and Sewell, M. C., *The Soil Mulch;* Jour. Amer. Soc. Agron., Vol. 9, No. 2, pp. 49-61, Feb., 1917.

[2] Mosier, J. G., and Gustafson, A. F., *Soil Moisture and Tillage for Corn;* Ill. Agr. Exp. Sta., Bul. 181, Apr., 1915.

The above data, which are amply corroborated by other investigations,[1] indicate that, with an uncropped light silt loam in a semi-arid region, the soil-mulch is of little practical importance in conserving moisture. Moreover, the results in Illinois as well as Kansas are no better on cropped land, the cultivation seemingly having little influence on either moisture content or crop yield. The importance of a good seedbed is very strikingly shown by the Illinois data, as is also the necessity of weed control. The weeds not only appropriate moisture that should go to the crop, but at the same time absorb nutrients that should be utilized in other ways.

Certain general conclusions are unavoidable in respect to a soil-mulch.[2] In the first place, a cropped cultivated soil seems no more effective in preventing evaporation than one that is cropped and uncultivated. Whether this extends to bare soil under all conditions has not been conclusively shown. In the second place, the elimination of weeds seems to be the most important benefit of cultivation. It must be remembered, however, that cultivation may exert some benefit on aëration of a heavy soil and certainly encourages granulation to a certain extent.

114. Summary of moisture control.—Moisture control seems to fall logically under three heads: (1) run-off, (2) drainage, and (3) evaporation. The detrimental influence of run-off over the surface is due to erosion, the loss of the water

[1] Young, H. J., *The Soil Mulch;* Nebr. Agr. Exp. Sta., 25th Ann. Rep., pp. 124-128, 1912.

Barker, P. B., *The Moisture Content of Field Soils Under Different Treatments;* Nebr. Agr. Exp. Sta., 25th Ann. Rep., pp. 106-110, 1912.

Cates, J. S., and Cox, H. R., *The Weed Factor in the Cultivation of Corn;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 257, 1912.

Alway, F. J., *Studies on the Relation of the Non-available Water of the Soil to the Hygroscopic Coefficient;* Nebr. Agr. Exp. Sta., Res. Bul. 3, 1913.

Burr, W. W., *The Storage and Use of Soil Moisture;* Nebr. Agr. Exp. Sta., Res. Bul. 5, 1914.

[2] See Call, L. E., and Sewell, M. C., *The Soil Mulch;* Jour. Amer. Soc. Agron., Vol. 9, No. 2, pp. 49-61, Feb., 1917.

itself being of minor importance. Similarly percolation loss is important because of the nutrients carried away, rather than because of the waste of the water. Since a certain amount of percolation must take place and because a water-logged soil is unsanitary for plants, rapid drainage is essential. Of the various methods available, tile drainage is the most satisfactory. Evaporation loss, as with run-off and percolation, can be but very slightly checked. The soil-mulch is important in that the cultivation necessary to produce it keeps down the weeds and in this manner it eliminates serious crop competition for nutrients and moisture.

CHAPTER XI

SOIL HEAT[1]

It is universally recognized that biological activity is an energy expression and that such activity will not continue unless certain temperature relations are maintained. With higher plants this heat relation has two phases, the temperature of the air and that of the soil. The former is clearly a climatic factor and, except on a small scale, is beyond the control of man. The temperature of the soil, in a similar way, is subject to no radical regulation, yet soil management methods provide means whereby certain small but biologically vital modifications can be made, climatically unimportant but practically worthy of careful consideration.

115. Importance of soil heat.—Normal plant growth is practically suspended at a temperature of 40° F., while the germination of most seeds does not take place even at this point. In general, it is poor practice to place certain seeds and plants in soil where growth activities will not occur at once, since bacteria and fungi, active at low temperatures, may sap their vitality and ultimately cause their destruction. Three groupings of higher plants may be made as far as their temperature relationships are concerned. Wheat represents the crops that germinate and grow at relatively low temperatures. Maize requires a medium temperature for proper growth, while pumpkins and melons typify crops, the heat requirements of which are very high. The following data

[1] For a bibliography of the literature of soil heat see Bouyoucos, G. J., *An Investigation of Soil Temperature and Some of the Most Important Factors Influencing It;* Mich. Agr. Exp. Sta., Tech. Bul. 17, pp. 194-196; 1913.

from Haberlandt[1] show the need of careful temperature control in the propagation of plants:

TABLE XLVI

GERMINATION TEMPERATURES

CROP	MINIMUM	OPTIMUM	MAXIMUM
Wheat	40° F	84° F	108° F
Maize	49	93	115
Pumpkin	52	93	115

GROWTH TEMPERATURES

CROP	MINIMUM	OPTIMUM	MAXIMUM
Wheat	32-40° F	77- 78° F	88- 98
Maize	40-51	88- 98	98-111
Pumpkin	51-60	98-111	111-122

Other desirable biological activities, especially those due to bacteria, are impeded if not brought entirely to a standstill by a temperature of 32° F. Such changes as decomposition of organic matter, the production of ammonia from nitrogenous organic matter, the formation of nitrate nitrogen from ammonia and the fixation of atmospheric nitrogen depend on heat conditions which, fortunately, are optimum for the development of higher plants.

Desirable chemical reactions in the soil are much retarded by low temperatures, heat greatly accelerating such phenomena. This is especially noticeable in the tropics where weathering is much more rapid and intense than in temperate regions. Much of the hydration, oxidation, carbonation and solution in a temperate climate occurs in the summer when high temperature lends its aid to such desirable reactions.

[1] Haberlandt, F., *Die Oberen und Unteren Temperaturgrenze für die Keimung der Wichtigeren Landwirthschaftlichen Sämereien;* Landw. Versuchs. Stat., Band 17, Seite 104-106, 1874.

The effect of heat on the physical changes within the soil is often vital. The influence that temperature variation exerts on percolation, evaporation, and capillary movement of soil-water; on diffusion of gases, vapors, and salts in solution; and on osmosis, surface tension and vapor tension phenomena, may serve as examples of such heat modifications. Moreover, successive freezing and thawing of the soil greatly aids in granulation and aëration. The aspirating effect of a slight change in temperature is so tremendous as often markedly to renew the oxygen supply of the furrow slice.

In order fully to understand the practical and scientific relationships involved in even a partial control of soil heat, a certain cycle of events must be recognized. The cycle begins with the acquisition of energy from the sun and the establishment of certain temperature relations which depend on absorption activity and the facility with which heat is transferred from place to place. The important chemical, physical, and biological transformations within the soil depend as much on such movements as on the intensity of the temperature factors. Much of the energy so involved is soon lost from the soil, returning again to the space from which it came. Thus the cycle is completed, having provided the temperature conditions necessary for successful crop production. (See Fig. 41.)

116. Insolation received by the soil.—The sun supplies practically all of the energy by means of which the soil maintains a temperature suitable for its normal activities. Energy from other sources is negligible. Radiation, the means by which this transfer is affected, is a free wave movement of some type. It is an oscillatory phenomenon, the space between the sun and the receiving body being, so far as is known, entirely unaffected. The length[1] of such oscillations varies from

[1] The approximate wave lengths are as follows:

Infra-red	.000270 to .000075 cm.
Light waves	.000075 to .000036 cm.
Ultra-violet	.000036 to .000019 cm.

the short ultra-violet rays, through the so-called light wave series to the long infra-red rays, the latter possessing the greatest heat possibilities. The insolation of energy received at the upper limits of the earth's atmosphere varies with the season and with the position chosen.[1]

Due to the gases of the atmosphere and especially to clouds and dust, only a small portion of the total insolation actually

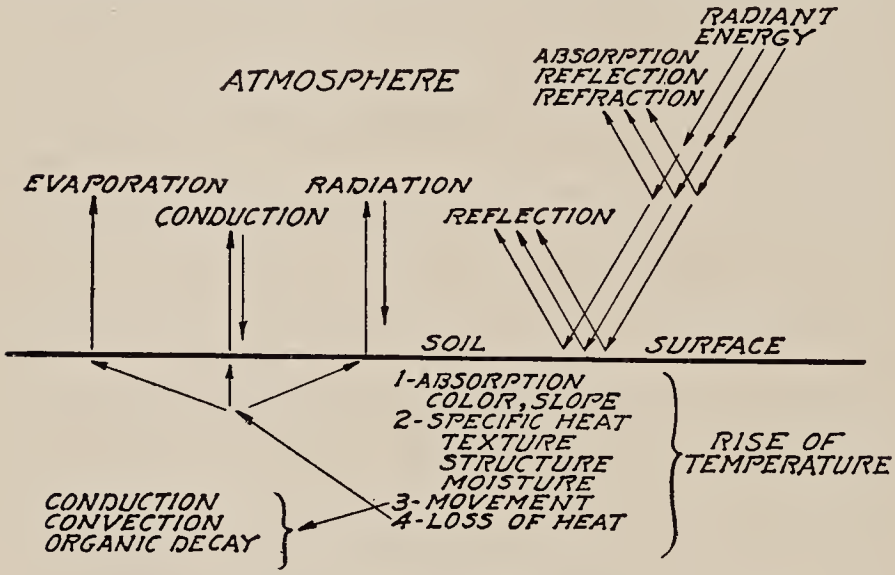


FIG. 41.—A diagram showing the heat relations of soil.

does work either on the land or water surfaces of the earth. The atmosphere and its impurities probably deflect on an average more than three-fourths of the insolation by absorption, reflection, and refraction. Little or none of such energy ever reaches the earth itself. Clouds and dust play an important rôle in such interception, affecting to a marked degree the energy received at any particular location. Part of the original insolation reaching the earth's surface is immediately reflected and is lost as radiant energy, having undergone no

[1] The earth and its atmosphere receives but one two-billionth of the sun's energy. On such a trifling proportion of the sun's energy depend almost all of the earth's activities.

transformation and, therefore, having done no work. This reflection is much greater on sea than on land and greater from snow than from soil surfaces. Reflection is influenced to a marked degree by vegetation, stubble, for example, being more effective than a green field, a forest or even bare soil. Possibly one-fifth of the earth's insolation on the average is absorbed by the land and water surfaees, being the source of the energy which later functions both statically and dynamically in the soil.

The statement is often made that warm rain carries considerable heat into the soil. Such an assertion is not only misleading but in most cases entirely incorrect. Precipitation in general is usually cooler than the soil in temperate regions, especially in the summer. Rain is spoken of as warm, not in comparison with soil but with average rain-water temperature. Even if rain water should be 10° F. warmer than the soil, a very improbable assumption, an average rain would raise the temperature of the surface six inches only slightly.

117. Absorption of insolation.—The energy reeeived from the sun functions in a number of ways on reaching the land surfaces of the earth. It may accelerate chemical reactions, it may be absorbed by plants, it may induce certain changes in form and, lastly, it may be converted into heat. It is in this latter state that insolation energy plays its most important part in soil activities, since heat energy may act in ways that radiant energy finds impossible. Since heat is commonly conceived as the kinetic energy of the molecules of a body, it is quite distinct and different from solar radiation, which must encounter some favorable substance before heat is produced. Temperature is the condition of a body in respect to its heat energy and is the common mode of expressing heat intensity.[1]

[1] Molecules are in constant motion, colliding with their neighbors, rebounding, and quivering. They possess energy which is called heat. Temperature is determined by the velocity of the molecules and is a manifestation of heat.

Certain inherent qualities of the soil as well as its position tend to influence its capacity to absorb radiant energy. The effect may be measured in the resultant rise in temperature, providing all variables are under control. The factors involved are texture, structure, color, and position. Only the last two are of practical importance.

118. Influence of color on absorption.—It is well known that a black surface absorbs more energy than a white one under similar conditions and will register a more rapid and a higher temperature rise. This is because of a difference in reflection, the white surface being more effective in this respect. The same principle has been shown by a number of investigators to hold with soil.[1] The addition of organic matter, provided its decomposition has been of the proper sort, will, other factors being equal, favor a higher soil temperature. Wollny[2] in experimenting with soil covered with thin layers of different colored material obtained some interesting field data. The black soil not only exhibited the highest temperature but also showed the greatest fluctuation. Minimum temperatures were the same regardless of color, while temperature differences decreased with depth. The curves in Fig. 42 are typical of Wollny's results on clear days.

Besides the quite obvious effect of color on rate of energy absorption, the curves exhibit two other points worthy of notice. The first is the tendency of the soil temperature to lag behind that of the air and the second is the equal minima reached by the two soils. The latter tendency would seem to indicate that color has little effect on the radiation of heat by soil.

[1] Bouyoucos, G. J., *An Investigation of Soil Temperature;* Mich. Agr. Exp. Sta., Tech. Bul. 17, p. 30, 1913.

Lang, C., *Über Warme-absorption und Emission des Boden;* Forsch. a. d. Gebiete d. Agr.-Physik., Band I, Seite 379-407, 1878.

[2] Wollny, E., *Untersuchung über den Einfluss der Farbe des Bodens auf dessen Erwärmung;* Forsch. a. d. Gebiete d. Agri.-Physik., Band I, Seite 43-69, 1878. Also, *Untersuchungen über den Einfluss der Farbe des Bordens auf dessen Erwärmung;* Forsch. a. a. Gebiete d. Agr.-Phys., Band IV, Seite 327-365, 1881.

119. The effect of slope on absorption.—The second phase to be considered in the rise of temperature of a given soil is the angle of incident of the sun's rays. The greater the inclination of a soil from a right angle interception, the less rapid will be the rise in temperature. As a consequence, the total insolation received in the tropics to a unit area is greater than that attained by a corresponding area in the temperate zone. Moreover, any condition in a temperature

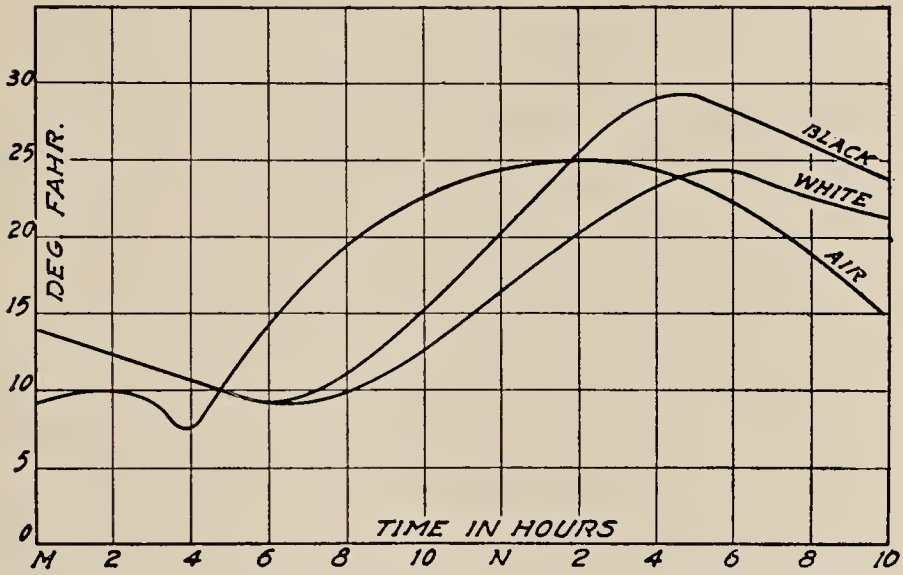


FIG. 42.—Curves showing the temperature variations of different colored soils at a four inch depth compared with air temperature. Munich, June 23, 1876.

region which tends to bring a unit surface more nearly normal to the sun's rays will increase its absorbed energy and raise its average seasonal temperature. In the north temperate zone this is of course a southerly inclination. The diagram (Fig. 43) illustrating conditions on the 42d parallel at noon on June 21 makes clear this relationship.

It is seen that in this case a southerly slope of 20° received the greatest amount of heat to a unit area with the level soil

next and the northerly slope last. The amount of heat for a given area is in the order of 106, 100, and 81, respectively.

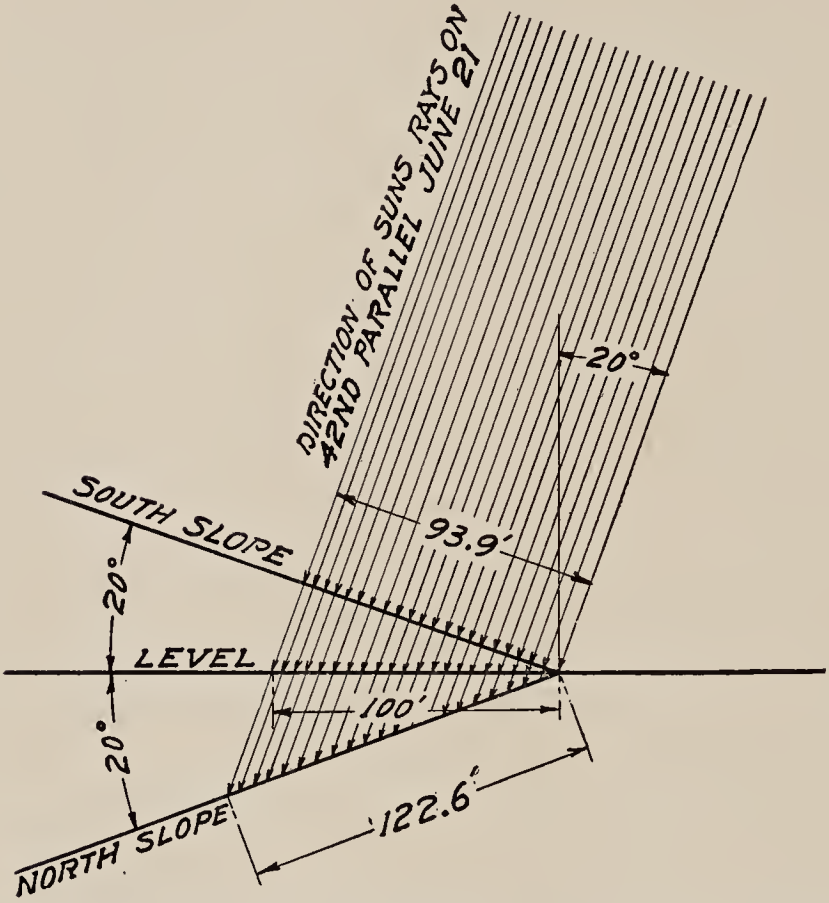


FIG. 43.—Diagram showing the distribution of a given amount of radiant energy on different slopes on June 21, at the 42nd parallel north.

These generalizations have been established by the work of a number of investigators.[1]

Wollny[2] found near Munich that the temperature of south-

[1] King, F. H., *Physics of Agriculture*, p. 218. Madison, Wis., 1910.
[2] Wollny, E., *Untersuchungen über den Einfluss der Exposition auf die*

ward slopes varied with the time of year. For example, the southeasterly inclination was warmest in the early season, the southerly slope during mid-season and the southwesterly slope in the fall. Such a relationship is of course governed entirely by local climatic conditions, especially cloudiness, and might not be true of any other place. A southeasterly slope is generally preferred by gardeners. Orchardists also pay strict attention to the aspect as it is often a factor in sun-scald and certain plant diseases.

120. Rise of temperature and the factors involved.—The rise of temperature of a layer of soil following a given absorption, depends (1) on the specific heat of the soil, (2) on the rate at which the heat moves to other parts of the soil mass, and (3) on the losses of heat to the atmosphere. It is evident that in a study of the influence of insolation on soil temperature, specific heat should receive the first attention.

121. Specific heat and soil temperature.—The specific heat of any material may be defined as its thermal capacity compared with that of water. It is expressed as a ratio to the quantity of heat required to raise the temperature of a given amount of a certain substance 1° C. to the quantity needed to change an equal amount of water from 15° to 16° C.

The specific heat figure for soil generally refers to the heat capacity of the dry substance. Under normal conditions, soils contain variable amounts of pore spaces and consequently have different weights to the cubic foot. A specific heat figure based on weight, therefore, does not give a true idea of the relative heat capacities of two soils. The expression of specific heat by volume seems a more rational basis of comparison.[1] The specific heat of the soil is important because of the relation it has to the warming up of soil in the spring, the

Erwärmung des Bodens; Forsch. a. d. Gebiete d. Agr.-Physik., Band I, Seite 263-294, 1878. This publication contains a number of other papers on this subject by Wollny.

[1] Weight specific heat of a substance may be expressed by the number of calories required to raise the temperature of one gram, 1° C. Volume

rate of cooling in autumn, drainage influences, and like phenomena.

Specific heat data from different investigators do not show the agreement that might be expected.[1] This is probably due (1) to inaccuracies in the naming of the soils used, (2) to difference in methods, and (3) to difficulties in technique. Everything considered, the following table from Ulrich [2] displays in a suitable way the important specific heat phases:

TABLE XLVII

VOLUME SPECIFIC HEAT OF SOIL

Soils	Weight Volume	Volume Specific Heat
Sand	1.52	.2901
Clay	1.04	.2333
Organic matter	.37	.1639

It is evident that specific heat is partially governed by the organic matter of the soil and partially by texture and struc-

specific heat is the number of calories necessary to raise the temperature of one cubic centimeter of the substance one degree. In the case of soil, weight specific heat may be changed to volume specific heat by multiplying it by the volume weight, since volume weight is the weight in grams of one cubic centimeter of dry soil.

[1] The following weight specific heats from Lang,* Patten † and Bouyoucos ‡ are interesting:

Lang		Patten		Bouyoucos	
Coarse sand	.198	Sand	.185	Sand	.193
Limestone soil	.249	Sandy loam	.183	Gravel	.204
Organic soil	.257	Loam	.191	Clay	.206
Garden soil	.276	Loam	.194	Loam	.215
Peat	.477	Clay	.210	Peat	.252

* Lang, C., *Über Wärme Capacität der Bodenconstituenten;* Forsch. a. d. Gebiete d. Agr.-Phys., Band I, Seite 109-147, 1878.

† Patten, H. E., *Heat Transferenee in Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 59, p. 34, 1909.

‡ Bouyoucos, G. J., *An Investigation of Soil Temperature;* Mich. Agr. Exp. Sta., Tech. Bul. 17, p. 12, 1913.

[2] Ulrich, R., *Untersuchungen über Wärmekapazität der Bodenkonstituenten;* Forsch. a. d. Gebiete d. Agr.-Phys., Band 17, Seite 1-31, 1894.

ture. Organic matter will lighten and loosen a soil, and lower the volume weight. Moreover, its heat capacity is low. The effect of such an addition is to lower the specific heat figure. It is apparent also that the finer the texture of the soil, the lower the specific heat. That is due not to a difference in chemical composition but to a lowered volume weight. Any practice, therefore, that tends to vary volume weight will in a like manner vary specific heat. The farmer may encourage the warming of his soil by deep and efficient plowing. By increasing its organic content, he may create a tendency in the same direction.

One other factor, more important than those already mentioned, yet remains to be discussed. This is water, so universally present in soils and so important in natural soil phenomena. As the specific heat of water is several times greater than that of the soil constituents, any addition of it must raise the thermal capacity of the mass. The following data from Ulrich[1] show that moisture rather than texture and organic matter is the controlling factor in normal soil:

TABLE XLVIII

THE EFFECT OF MOISTURE ON VOLUME SPECIFIC HEAT OF SOIL (MOISTURE EXPRESSED AS A PERCENTAGE OF THE TOTAL WATER CAPACITY)

	Dry Soil	10% Water	20% Water	40% Water	60% Water	80% Water	100% Water
Sand.....	.291	.330	.368	.444	.520	.597	.675
Clay.....	.233	.294	.355	.478	.600	.723	.845
Organic matter	.164	.242	.320	.476	.632	.788	.945

The overwhelming influence of moisture is at once evident from these data. Fine texture, because of its high water capacity, usually accentuates the dominance of moisture. Organic matter functions in the same way. While an organic

[1] Ulrich, R., *Untersuchungen über die Wärmekapazität der Bodenkonstituenten;* Forsch. a. d. Gebiete d. Agr.-Phys., Band 17, Seite 27, 1894.

soil of low volume weight may warm up easily when dry, its high water content usually markedly retards its temperature change. A muck soil is usually the last to freeze in winter and, conversely, the last to thaw in spring. The advantage of drainage is evident as a wet soil is of necessity colder in the spring than one that is well drained. This at least partially accounts for the fact that a sandy soil is usually an early one and is, therefore, of particular value in trucking.

122. Heat movements in soil.—While volume weight, organic matter, and moisture seem largely to control the degree to which a soil will become heated when exposed to insolation, it is evident that there must be some mode of energy transfer whereby such phenomena may be facilitated. Heat movement is necessary in order that the lower layers of the soil may become warm enough for proper biological functionings. Energy transmission both downward and laterally is absolutely essential and deserves as much attention as the factors influencing insolation absorption.

Two methods of heat transfer function in a normal soil—conduction and convection. These modes of energy movement are extremely difficult to analyze, due to the impossibility of controlling one while studying the other.

123. Conduction of heat in soil.—While radiation has to do with the oscillatory transfer of energy conduction relates to the molecular transmission of heat through any material. When one part of a substance is heated, the movement of its molecules is stimulated. These molecules strike their neighbors with increased force, thus quickening their motion. These in turn accelerate others until the energy applied at one point becomes apparent at another. Solids as a class are better conductors than liquids, while liquids in general are superior to gases in this respect. It must be remembered in studying the conductivity of heat through soil, that we are dealing with a heterogeneous mixture of mineral and organic matter containing varying amounts of air and water. The movement

of soil heat involves not only the question of conduction through solids but through liquids and gases as well. Moreover, transfer resistance, which occurs at the boundary of two substances in contact, has much to do with the rate of transmission. In addition, the air and water of the soil are capable of considerable movement which makes conductivity studies extremely difficult due to convection currents.

The heat conductivity of soil is affected by a number of factors which may or may not lend themselves to field control. Important among these are texture, structure, organic matter, and moisture. The influence of the first is clearly shown by the following comparative data obtained by Bouyoucos,[1] with field soils:

TABLE XLIX

RELATIVE CONDUCTIVITY AS MEASURED BY THE TIME REQUIRED FOR A THERMOMETER 7 INCHES FROM THE SOURCE OF HEAT TO INDICATE A RISE IN TEMPERATURE

Soil	Relative Rate of Conductivity
Sand	100
Loam	150
Clay	143
Peat	362

These results are comparative only in a qualitative way. Quantitative determinations are so beset by error that only few investigators have made any consistent attempt along this line. Patten's results [2] expressed as metric K [3] (the heat con-

[1] Bouyoucos, G. J., *An Investigation of Soil Temperature;* Mich. Agr. Exp. Sta., Tech. Bul. 17, p. 20, 1913.

[2] Patten, H. E., *Heat Transfer in Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 59, p. 26-28, 1909.

[3] The conductivity of a substance is measured by the number of gram-calories of heat transmitted in 1 second through a cube with 1 centimeter edges, when the opposite faces differ in temperature by 1°C. The calories of heat transmitted (H) will be proportional to the area of the

ductivity coefficient in C.G.S. units) shows the same general comparisons as already presented:

TABLE L

CONDUCTIVITY COEFFICIENTS OF DIFFERENT DRY SOILS

SOILS	K
Coarse quartz	.000917
Leonardtown loam	.000882
Podunk fine sandy loam	.000792
Hagerstown loam	.000699
Galveston clay	.000577
Muck	.000349

It is evident, in general, that the finer the texture of the soil, the lower is the conductivity. This cannot be construed as indicating that the conductivity coefficients of sand and clay particles are particularly different. The variance observed is adequately explained by the great number of transfers necessary in a fine-textured soil. It is also evident that the addition of organic matter will lower conductivity. Humus itself has a low conductivity coefficient and would markedly affect the transfer resistance by changing the structure of the soil. Compacting a soil should accelerate heat transfer due to a more intimate contact of the soil grains and a consequent diminution of transfer interference. Tillage, on the contrary, must impede not only the movement of heat downward in the soil but from the subsoil into the furrow slice.

The greatest single factor to be considered in heat conductivity is the moisture content of the soil. The curve (Fig. 44)

faces (A) and to the differences in temperature of the faces (t'—t"), while it will be inversely proportional to the thickness (d) of the cube. K is a constant, depending on the material studied.

$$H = K \frac{A\,(t'-t'')}{d}$$

for fine sandy loam, constructed from Patten's data,[1] illustrates its effect and indicates how heavily it must override the factors already mentioned:

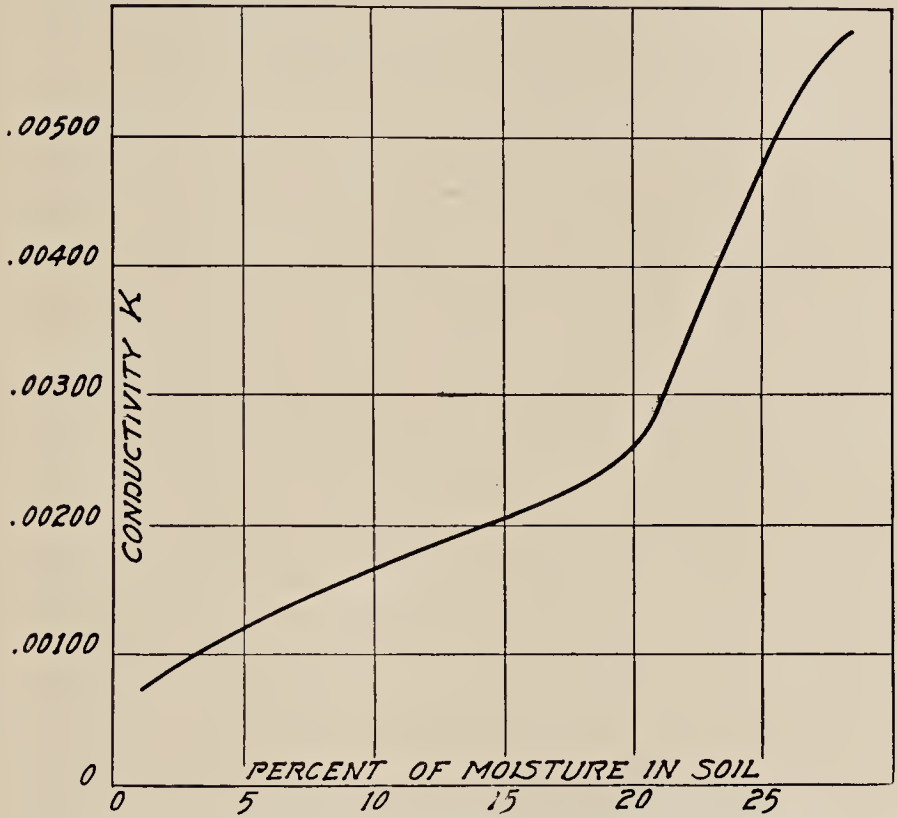


FIG. 44.—Conductivity curve for Podunk fine sandy loam, showing the influence of moisture content upon the rate of heat transfer. The curve apparently flattens out at a high moisture content indicating that good conductivity may be obtained at optimum moisture.

At first glance it appears peculiar that the heat movement through a soil, the mineral constituents of which possess a conductivity coefficient of about .01066, should be accelerated by the addition of a liquid possessing a value for K of about .00149. The explanation lies in the lowering of the transfer

[1] Patten, H. E., *Heat Transfer in Soils;* U. S. Dept. Agr., Bur. Soils, Bull. 59, p. 27, 1909.

resistance. Heat passes from soil to water about 150 times easier than from soil to air. As the water increases, the air decreases and the rate of conductivity is raised. When sufficient water is present to join all of the soil particles, further additions will have little effect on character of heat movement. Moisture, optimum for crop growth, amply provides for heat transfer. The slow warming up of the lower subsoil must not be taken as an indication of lower conductivity. It is due rather to a lessened heat supply. As a matter of fact, the rate of heat transmission has been shown to be more rapid in the subsoil, due to a greater compaction and to the presence of more water.

This brief discussion of conductivity shows the vital importance of such a phenomenon to plants in that the necessary heat is carried broadcast through the soil. While conductivity is affected to a certain extent by texture, structure, and organic matter, moisture is the dominant factor. Under natural conditions, it is necessary to maintain a medium amount of water in the soil. This moisture condition, fortunately, supports almost maximum heat conduction. Good tilth and increased organic matter probably exert their greatest influence on this type of heat transfer by their influence on soil moisture.

124. Convection transfer of heat.—Convection, the third manner by which energy may be conveyed, is a heat transfer by means of currents in liquids or gases. It functions by an actual and obvious movement of matter. In the soil absorption tends to heat the air as well as the solid substance. This produces currents due to the expansion and rise of the warmed gases. It is obvious that such heat movement must always be lateral or upward, never downward. Such convection exerts its greatest influence in equalizing the temperature of the soil, overcoming the effects of unequal conduction and uneven absorption due to vegetation or stone. Air currents as they escape into the upper air carry considerable heat away from

the soil. Such a loss is of little moment, however, compared to that continually occurring through conduction and radiation.

Some heat is carried downward into the soil by percolating water. This is a true convection activity. The importance of such a heat transfer is only conjectural. As percolation is generally intermittent in a soil, it is probable that it does not modify to any extent the influence exerted by conduction.

125. Effect of organic matter on soil temperature.— Plants entrap a considerable amount of radiant energy from the sun, part of which is utilized during the growth period. The remainder exists as latent energy in the tissue. If any amount of plant remains are incorporated in the soil and decay proceeds, this heat is liberated. Thus a heat transfer is similar in a way to convection, except that, in this case, the transfer is by the movement of a solid and the energy is latent.

To what extent the decay of organic matter is effective in bringing about any important modification of field soil, it is difficult to say. In greenhouses and hotbeds perceptible increases are obtained by the use of fresh manure. In the field, however, where the absorption and loss of heat are very large and where the organic matter makes up but a small portion of the soil mass, it is doubtful whether any important heat increase occurs. Georgeson,[1] in Japan during the first twenty days after an application of eighty tons of manure to the acre, obtained an increase of only 3.4° F. over a soil untreated. Wagner [2] found an average increase of 1° F. from the use of twenty tons of barnyard manure to the acre. Bouyoucos [3] has obtained the latest data on the subject. Under

[1] Georgeson, C. C., *Influence of Manure on Soil Temperature;* Agri. Sci., Vol. 1, pp. 25-52, 1887.

[2] Wagner, F., *Über den Einfluss der Dungung mit Organischen Substance auf die Bodentemperatur;* Forsch. a. d. Gebiete d. Agr.-Phys., Band V, Seite 373-405, 1882.

[3] Bouyoucos, G. J., *An Investigation of Soil Temperature;* Mich. Agr. Exp. Sta., Tech. Bul. 17, pp. 180-190, 1913.

carefully controlled conditions, he found that unless excessive amounts of manure were added no appreciable effects were observed. Such results indicate that the heat of decay and fermentation has little practical effect in modifying the temperature of field soils. Without doubt there are certain localized influences, but how important they may be is beyond our present knowledge. As far as heat relations are concerned, it seems that organic matter exerts its greatest effects through a darkening of the color and an increase in the moisture capacity of the soil.

126. Loss of heat—conduction, radiation, and evaporation.—Although small amounts of heat may be carried from the soil by percolating water, the only important loss is into the atmosphere above. This loss occurs in three ways, conduction, radiation, and evaporation. The loss due to evaporation is easily the least important of the three. Conduction and radiation have much to do with climatic control, since the atmosphere receives its energy in large degree from the earth rather than directly from the sun. Conduction from soil to air and *vice versa* can be modified but to a slight extent by man, a fortunate provision of nature.

Terrestrial bodies are continually radiating energy waves into the atmosphere, the change of temperature depending on whether the receipt of such oscillations exceeds or falls short of the loss. In the case of the soil, there is a very great dissipation of energy in this way, radiation with conduction being important climatic controls. The rapid changes in air temperature are often directly due to these phenomena.

These energy waves of terrestrial origin are very long,[1] being within the infra-red group and consequently make no impression on the eye. They are often spoken of as the dark rays. Their energy capacity is higher than that of shorter oscillations. The trapping of heat in a greenhouse

[1] Terrestrial bodies at ordinary temperatures give out waves varying in length from .000270 to .001500 cm. The warmer the body, the shorter the wave length.

is partially due to the tendency of the objects within the house to give off these long rays, which do not pass through the glass with the facility possessed by the shorter vibrations by means of which a large proportion of the energy was introduced.

The texture, structure, and color of the soil have little influence on radiation. Moisture tends to hasten it a trifle, since water is a better radiator than soil. Mulches, as they are loose and dry, may check radiation slightly. Artificial coverings, shelters, and clouds seem to exert the greatest effect. It is often feasible to protect plants from frost by interfering with radiation and conduction. Clouds by shutting in heat, may in some cases prevent a frost that would otherwise occur, due to the rapid cooling. Snow likewise has a protecting effect and may often prevent the soil underneath from freezing. While man may influence radiation locally, it is evident that the total energy loss can be checked but little.

The effect of evaporation on the temperature of the soil is especially noticeable because of its rapid action. This vaporization of water is caused by an increased molecular activity and requires the expenditure of a certain amount of heat,[1] which results in a cooling effect on the water remaining and consequently on the soil and air with which it is in contact. It requires 267.9 kilogram calories to evaporate one pound of water at 50° F. This is sufficient to lower the temperature of a cubic foot of saturated clay about 20° F., providing that all of the energy of evaporation comes from the soil and its water.

The low temperature of a wet soil is due partially to evaporation and partially to high specific heat. King [2] found during

[1] It requires 536.6 gram-calories to evaporate one gram of water at 100°C., while 596.7 calories are necessary if evaporation takes place at 0°C. The calories (C) required to vaporize one gram of water at any temperature (t) may be calculated by the formula:

$$C = 596.73 - .601\ t$$

[2] King, F. H., *Physics of Agriculture,* p. 20; Madison, Wis., 1910.

April that an undrained soil in Wisconsin ranged from 2.5°F. to 12.5° F. lower than one of the same type well drained. Parks [1] reports data of the same order from England. Drained and undrained soil held in trays at Urbana, Illinois,[2] showed maximum differences of 13.7° F., 9.0° F., and 6.2° F. at depths of 1, 2, and 4 inches, respectively. The differences were greatest in the day. Wollny considers that the depression of temperature due to evaporation is roughly proportioned to the moisture present. Texture, structure, and organic matter influence the cooling action of evaporation, since they exert such a marked effect on water capacity and capillary movement. The practical importance of evaporation study lies in the fact that it can be controlled to such a marked extent in the field. Such is not true of radiation and conduction. Windbreaks and shelters have been shown by King [3] to reduce evaporation over short distances as much as 25 per cent. This means a conservation of soil energy for the time being. Thorough under-drainage not only checks evaporation losses but lowers the specific heat of the soil, retards its radiation and facilitates convection. This means a faster warming up, especially of the root zone. Optimum moisture encourages optimum heat conditions as well as other favorable phenomena. Drainage, tillage, and organic matter are the dominant factors in this moisture control.

127. Soil temperature and its variations.—The temperature of the soil at any time depends on the ratio of the energy absorbed and the heat being lost. The constant change in this coördination is reflected in the seasonal, monthly, and daily soil temperatures. The following data [4] are representa-

[1] Parks, J., *On the Influence of Water on the Temperature of Soils;* Jour. Roy. Agr. Soc. Eng., Vol. 5, pp. 119-146, 1845.

[2] Mosier, J. G., and Gustafson, A. F., *Soil Physics and Management;* p. 302; Philadelphia, 1917.

[3] King, F. H., *The Soil,* p. 189; New York, 1906.

[4] Swezey, G. D., *Soil Temperatures of Lincoln, Nebraska;* Nebr. Agr. Exp. Sta., 16th Ann. Rep., pp. 95-102, 1903.

tive of soil temperatures in temperate climates with moderate rainfall:

TABLE LI

AVERAGE TEMPERATURE READINGS TAKEN AT LINCOLN, NEBRASKA, 1890-1902. DEGREES FAHRENHEIT

SEASON	AIR	1 INCH DEEP	3 INCHES DEEP	6 INCHES DEEP	12 INCHES DEEP	24 INCHES DEEP	36 INCHES DEEP
Winter	25.9	28.8	28.8	29.5	32.2	36.3	39.1
Spring	49.9	54.8	53.6	51.6	48.5	45.7	44.3
Summer...	73.8	83.0	80.9	79.1	73.8	69.0	66.2
Autumn...	53.9	56.4	57.6	57.1	57.5	59.3	60.3

It is apparent that the seasonal variations of temperature are considerable even at the lower depths. The surface layers vary more or less in accord with the air temperature and, therefore, exhibit a greater fluctuation than the subsoil. In general, the surface soil is warmer in spring and summer than the lower layers but cooler in fall and winter. The soil, on the average, is warmer than the air in winter. This occurs because the air responds more quickly to a change in solar insolation than the soil.

The curves showing the monthly march of soil temperature at Lincoln, Nebraska (Fig. 45), reveal the lag of the temperature change in the subsoil due to slow heat penetration. It is also noticeable that the monthly range in temperature change in the surface soil is higher than that of the air. The absolute range is, of course, greater for the air. It must be kept in mind that changes in soil temperature are gradual, while the air may vary many degrees in an hour.

The daily and hourly temperature of the air and soil in the temperate zone may show considerable agreement or marked divergence according to whether the weather control is cyclonic or solar. With solar control and a clear sky the air temperature rises from morning to a maximum at about

two o'clock. It then falls rapidly. The soil, however, does not reach its maximum temperature until later in the afternoon, due to the usual soil lag. This retardation is greater and the temperature change less as the depth increases.[1] The substratum of a soil shows little daily, or even monthly, variation and is affected, if at all, by seasonal changes only. The

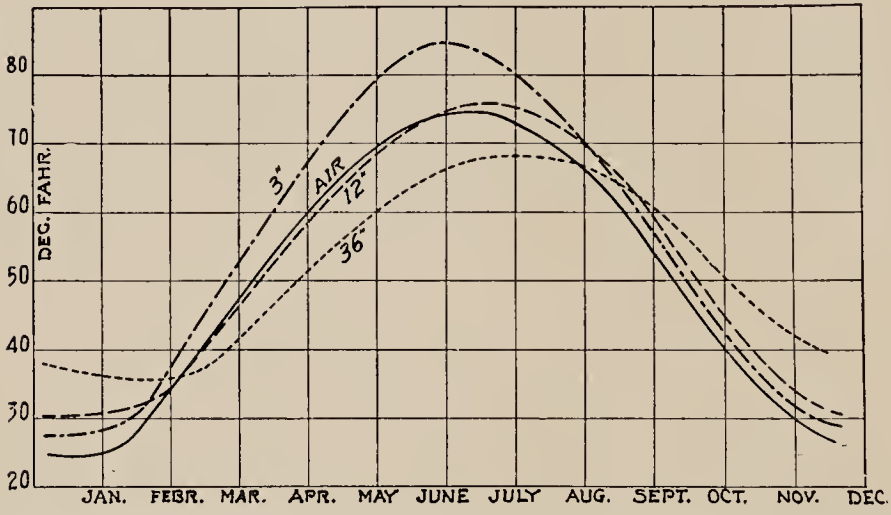


FIG. 45.—Curves showing the average monthly temperature readings at various soil depths. Average of twelve years, Lincoln, Nebraska.

curves in Fig. 46, comparing soil and air temperatures at Munich[2] on a bright day in May, substantiates some of the statements above:

128. Control of soil temperature.—The most important factor in the control of soil heat is obviously moisture. Good

[1] The following laws hold in a general way:

1. The lag of the temperature wave is proportional to the depth.

2. The diurnal amplitude of the temperature oscillation decreases in geometric progression as the depth increases in arithmetic progression. If the temperature variation at the surface was 24°F and at 6 inches deep 12°F, according to this law the diurnal variation at 12 inches would be 6°F and at 18 inches 3°F.

[2] Wollny, E., *Untersuchungen über den Einfluss der Pflanzendecke und der Beschattung auf die Physikalischen Eigenschaften des Boden;* Forsch. a. d. Gebiete d. Agr.-Physik., Band VI, Seite 197-256, 1885.

drainage, and a proper structural development, sufficient organic matter and deep and careful plowing, favor optimum moisture conditions. Such moisture regulation means a lowered specific heat, rapid conductivity, and good convection. The increase of soil organic matter may act directly in heat control by darkening the color and thus increasing absorp-

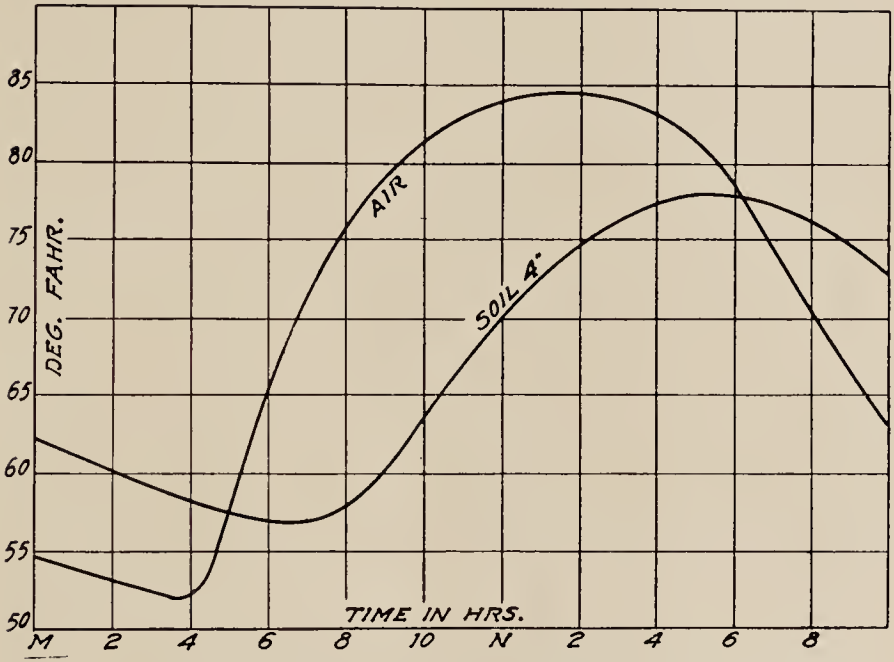


FIG. 46.—Curves showing the hourly temperature of a bare soil at a depth of four inches and of the air just above the soil in Germany, May 26. (Data from Wollny.)

tion. A soil-mulch, being dry, not only may check evaporation but at the same time may lower radiation.

Any method of handling the land which tends to benefit its physical condition, better its tilth and control its moisture, tends at the same time towards a proper heat control. The whole question may be summarized by saying that, if a farmer adopts a proper system of moisture control and at the same time employs methods that continually encourage a better

physical condition of the soil, the problem of the control of soil heat will be solved automatically. The farmer will then have brought about the best conditions for heat absorption and will have facilitated conduction and convection, retarding at the same time losses by evaporation and radiation.

CHAPTER XII

SOIL AIR

The soil is a porous mass of material of which only about one-half is solid matter. The pore space that results is occupied by water and by air in a constantly varying proportion. When a soil is in good condition for crop growth, the air space rarely makes up more than from 20 to 25 per cent. of its volume. The texture of the soil and the amount of moisture are obviously the main controls. The individual air spaces of the soil are more or less continuous and seem to maintain a fairly complete communication between the various horizons. The better the granulation of the soil and the greater the number of cracks and burrows, the easier and quicker is this communication. The air of the soil is either directly in contact with the roots and the soil bacteria or separated from them by only a thin layer of moisture or colloidal material.

The air of the soil is not merely a continuation of the atmospheric air into the interstitial spaces. As it is enclosed by the soil complexes and by the soil-moisture movement does not take place readily. Hence it is greatly influenced by its local surroundings. This leads to important differences between the atmospheric air and the soil air, the character of the latter depending on a variety of conditions in which the physical, chemical and biological properties of the soil play a large part.

129. Composition of soil air.—The air of the soil differs from that of the outside atmosphere in that it contains more water-vapor, a much larger proportion of carbon dioxide, a

correspondingly smaller amount of oxygen, and slightly larger quantities of other gases, including ammonia, methane, hydrogen sulfide, and the like, formed by the decomposition of organic matter. The percentage of nitrogen is practically the same in all cases. The following average data quoted from three different sources show the comparative compositions as far as the carbon dioxide, oxygen, and nitrogen are concerned. All other gases are included with the nitrogen figures.[1]

TABLE LII

AVERAGE COMPOSITION OF SOIL AIR AND ATMOSPHERIC AIR

LOCATION	PERCENTAGE BY VOLUME		
	CO_2	O_2	N_2
Soil Air			
Germany [2]	.20	20.60	79.20
Iowa [3]	.20	20.40	79.40
England [4]	.25	20.65	79.20
Atmospheric Air			
England [4]	.03	20.97	79.0

Russell and Appleyard,[5] in their study of the soil atmosphere, found that there are really two types of soil air. The first one occupies the portion of the pore space not taken

[1] Atmosphere air carries about .93 per cent. of argon, with very small amounts of other inert gases such as krypton, xenon, helium and neon. These gases are of course present in the soil.

[2] Lau, E., *Beiträge zur Kenntnis der Zusammensetzung der im Ackerboden befindlichen Luft;* Inaug. Diss., Rostock, 1906.

[3] Jodidi, S. L., and Wells, A. A., *Influence of Various Factors on Decomposition of Soil Organic Matter;* Ia. Agr. Exp. Sta., Res. Bul. No. 3, Oct. 1911.

[4] Russell, E. J., and Appleyard, A., *The Atmosphere of the Soil: Its Composition and the Causes of Variation;* Jour. Agr. Sci., Vol. VII, Part 1, pp. 1-48, 1915.

[5] Russell, E. J., and Appleyard, A., *The Atmosphere of the Soil: Its Composition and the Causes of Variation;* Jour. Agr. Sci., Vol VII, Part 1, pp. 1-48, 1915.

up by water, is free to move from place to place and is saturated or nearly saturated with water-vapor. It is the soil atmosphere most commonly referred to and its composition is set forth in the above tabulation. After this air was drawn off Russell and Appleyard found that still more air could be removed by applying suction. This air at first carried considerable oxygen but by continuing the suction almost pure carbon dioxide was obtained. The amount of gas removed by lowering the pressure varied directly with the moisture content of the soil and consequently it may be considered as air largely absorbed by the moisture of the soil complexes.

Two types of atmosphere, therefore, exist in the soil. One, the ordinary soil air, is comparatively rich in oxygen. The other, absorbed by the soil moisture, is very low in oxygen but very high in carbon dioxide. Obviously they insensibly merge. The biological significance of these atmospheric types is very important. Their simultaneous presence admits of both aërobic and anaërobic biological activity. For example, rapid nitrate formation might be progressing but no accumulation would be evident, due to just as rapid a synthetic activity of the anaërobic forms.[1]

It must not be assumed from the data above quoted that the composition of the soil air is at all constant or that it is approximately the same in every soil. The soil is dynamic in nearly every phase and is nowhere more changeable than in its atmospheric composition. This variability will of course be more marked and more important in the air which occupies the interstitial spaces, although the absorbed air will show some fluctuation. The compositions of the air of several soils, as determined by Boussingault and Lewy[2] are quoted in the following table:

[1] Gainey, P. L., *Real and Apparent Nitrifying Power of Soils;* Science, N. S., Vol. 39, pp. 35-37, 1914.

Doryland, C. J. T., *Influence of Energy Material upon the Relation of Soil Microörganisms to Soluble Plant Food;* N. Dak. Agr. Exp. Sta., Bul. 116, pp. 318-399, 1916.

[2] Johnson, S. W., *How Crops Feed,* p. 219; New York, 1891.

TABLE LIII

CHARACTER OF SOIL	PERCENTAGE BY VOLUME		
	CO_2	O_2	N_2
Sandy subsoil of forest.....	.24	——	——
Loamy subsoil of forest.....	.79	19.66	79.55
Surface soil of forest.....	.87	19.61	79.52
Clay soil.....	.66	19.99	79.35
Soil one year after manuring	.74	19.02	80.24
Soil freshly manured.....	1.54	18.80	79.66
Vegetable mold compost.....	3.64	16.45	79.91

The differences in the composition of the atmosphere of different soils and the variability noticeable within the same soil are due primarily to two factors: (1) the production of carbon dioxide, and (2) oxidation. These will be discussed in the above mentioned order.

130. The carbon dioxide of the soil air.—The presence of carbon dioxide in soils may be due in small part to infiltration from the atmospheric air, there being a tendency for the carbon dioxide, which is heavier than nitrogen and oxygen, to settle out. It may also have a purely chemical origin. The latter source is much more probable. The absorption of the bases of carbonates or bicarbonates would obviously release carbon dioxide. This probably does not take place, however, to any great extent in a natural soil. When ground limestone is added, such a reaction does occur.[1] Carbon dioxide in appreciable amounts might for a short time thus be liberated through chemical reaction. The addition

[1] MacIntire, W. H., *The Carbonation of Burnt Lime in Soils;* Soil Sci., Vol. VII, No. 5, pp. 325-446, 1919. See also, *The Non-existence of Magnesium Carbonate in Humid Soils;* Tenn. Agr. Exp. Sta., Bul. 107, 1914.

of lime has been shown by several investigators to increase the carbon dioxide production.[1]

There is now no doubt that biological activities are largely

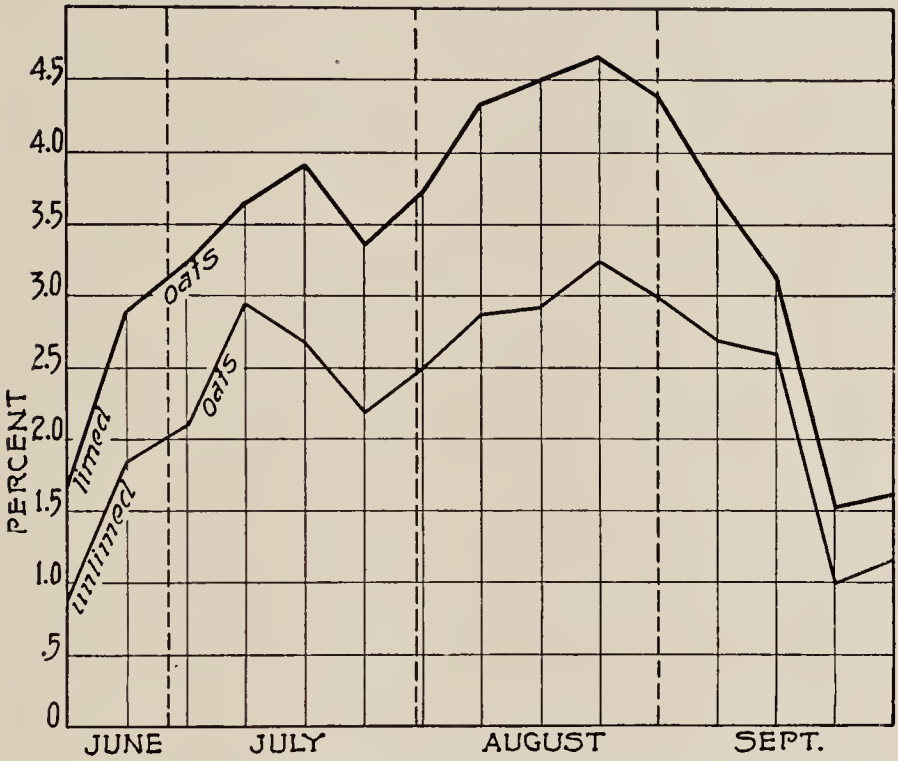


FIG. 47.—Diagram showing the amount of carbon dioxide in air from Volusia silt loam limed and unlimed and cropped to oats.

responsible for the occurrence of the large quantity of carbon dioxide in the soil air. There are two distinct processes in-

[1] Bizzell, J. A., and Lyon, T. L., *The Effect of Certain Factors on the Carbon Dioxide Content of Soil Air;* Amer. Soc. Agron., Vol. 10, No. 3, pp. 97-112; Mar. 1918.

Potter, R. S., and Snyder, R. S., *Carbon Dioxide Production in Soils and Carbon and Nitrogen Changes in Soils Variously Treated;* Ia. Agr. Exp. Sta., Res. Bul. 39; Feb. 1916.

Plummer, J. K., *Some Effects of Oxygen and Carbon Dioxide on Nitrification and Ammonification in Soils;* Cornell Agr. Exp. Sta., Bul. 384; Dec. 1916.

volved: (1) the physiological action of bacteria by which they absorb oxygen and give off carbon dioxide, and (2) the excretion of carbon dioxide by roots. (See Fig. 47.)

Recent work[1] has clearly shown that higher plants, especially during their most rapid growth, markedly increase the amount of carbon dioxide gas in the soil. Stoklasa[2] concluded that the microörganisms in an acre of soil to a depth of four feet may produce between sixty-five and seventy pounds of carbon dioxide a day for two hundred days in the year, and that during the growing period the roots of oats or wheat would give off nearly as much more. Turpin[3] finds that the crop often produces, during its period of active growth, many times as much carbon dioxide as is produced by soil organisms. He minimizes the influence of the decaying root particles of the crop occupying the soil on the carbon dioxide content of the soil air.

In any particular soil, the two major controls of carbon dioxide production seem to be temperature and rainfall.[4] The former apparently is dominant in a temperate humid region from November to May. During the remainder of the year, the moisture content of the soil and the amount of rainfall are the direct controls. Bacterial numbers and nitrate ac-

[1] Stoklasa, J., and Ernest, A., *Beiträge zur Lösung der Frage der Chemischen Natur des Wurzelsekretes;* Jahr. Wiss. Bot., Bd. 46, Seite 55-102, 1909.

Aberson, J. H., *Ein Beitrag zur Kenntnis der Natur der Wurzelausscheidunger;* Jahr. Wiss. Bot., Bd. 47, Seite 41-56, 1910.

Russell, E. J., and Appleyard, A., *The Influence of Soil Conditions on the Decomposition of Organic Matter in the Soil;* Jour. Agr. Sci., Vol. VII, Part 3, pp. 385-417, 1917.

Bizzell, J. A., and Lyon, T. L., *The Effect of Certain Factors on the Carbon Dioxide Content of Soil Air;* Amer. Soc. Agron., Vol. 10, No. 3, pp. 97-112, Mar. 1918.

[2] Stoklasa, J., *Methoden zur Bestimmung der Atmungsintensität der Bakterien im Boden.* Zeit, f. d. Landw. Versuchswesen in Oesterreich, Band 14, Seite 1243-79, 1911.

[3] Turpin, H. W., *The Carbon Dioxide of the Soil Air;* Cornell Agr. Exp. Sta., Memoir 32, April 1920.

[4] Russell, E. J., and Appleyard, A., *The Atmosphere of the Soil: Its Composition and the Causes of Variation;* Jour. Agr. Sci., Vol. VII, Part 1, pp. 1-48, 1915.

cumulation seem to fluctuate with the carbon dioxide, while the oxygen curve is almost the exact reciprocal. Other influences of a minor nature enter in, such as the character of the crop growing on the soil, heavy rainfall, oxygen dissolved in the rain, and rapid changes of temperature. (See Fig. 48.)

While plowing, application of lime, drainage, and other practices have a great influence on the proportion of oxygen

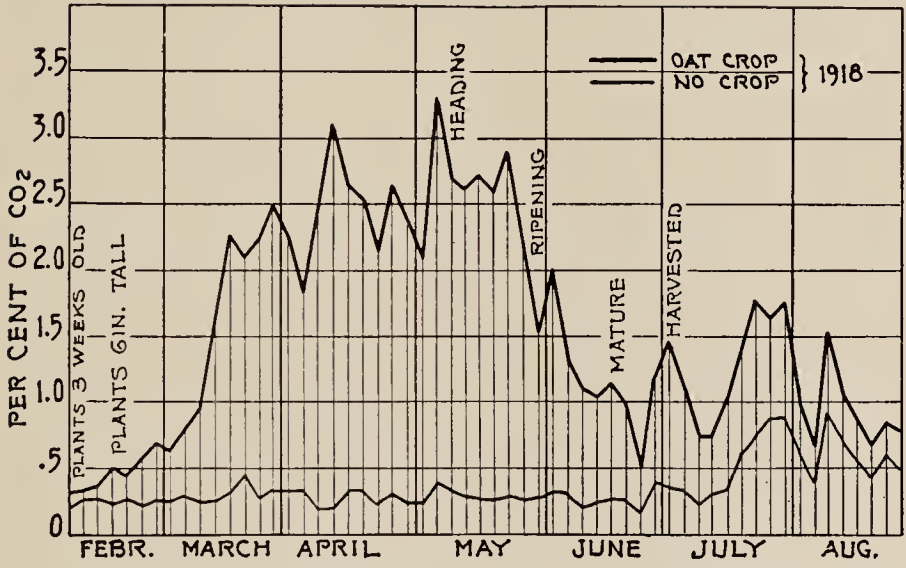


FIG. 48.—Carbon dioxide in air from Dunkirk clay loam bare and from the same soil cropped to oats, 1918. (After Turpin.)

and carbon dioxide in the soil air, the addition of organic matter seems to have the most profound effect. At the Rothamsted Experiment Station,[1] the carbon dioxide content of the air from two soils was studied. One soil (Broadbalk field) had been manured for a number of years while the other (Hoos) had not received such a treatment:

[1] Russell, E. J., and Appleyard, A., *The Atmosphere of the Soil: Its Composition and the Causes of Variation;* Jour. Agr. Sci., Vol. VII, Part 1, p. 25, 1915.

TABLE LIV

EFFECT OF FARM MANURE ON THE CARBON DIOXIDE CONTENT OF SOIL AIR. ROTHAMSTED, ENGLAND

TREATMENT	PERCENTAGE OF CO_2 BY VOLUME					
	MAY 15	MAY 25	JUNE 10	JUNE 12	JULY 7	JULY 27
Manured soil.....	.22	.32	.17	.36	.36	.35
Unmanured soil...	.10	.07	.08	.07	.08	.09

Although the formation of carbon dioxide in the soil is influenced to a marked degree by the decomposition of organic matter, the effect is by no means proportional to the quantity of organic matter present. The rate of decomposition varies greatly, and where this is depressed, as sometimes occurs in muck or forest soils, the content of carbon dioxide is relatively low. A high percentage of organic matter is in itself likely to prevent a proportional formation of carbon dioxide, since the accumulation of the gas may inhibit further activity of the decomposing organisms.

131. Oxidation and its effect on the composition of the soil air.—Oxidative processes in the soil are of two general types, those due to chemical reactions alone and those due to biochemical transformations. The purely chemical oxidation may be illustrated best by recalling the processes of soil formation.[1] Here it was noted that certain minerals, especially those carrying iron, were susceptible to the influence of oxygen. The following reactions show how olivine may assume water and then produce ferric oxide through oxidation:

$$3MgFeSiO_4 + 2H_2O = H_4Mg_3Si_2O_9 + SiO_2 + 3FeO$$
$$4FeO + O_2 = 2Fe_2O_3$$

This is illustrative of the complex reactions which are continually taking place and which tend materially to decrease the oxygen of the soil air.

[1] See Chapter II, par. 16, of this text.

Biochemical oxidation, however, is usually rapid and is a much more important factor in the oxygen control of the air. Not only do all bacteria require oxygen for their growth, but they are continually producing compounds that require oxygen in their molecules. Carbon dioxide is an oxidation product. Its formation reduces the oxygen of the air and its presence causes a dilution. Sulfofication and nitrification are well known examples. The reactions for the process of nitrification illustrate in addition the production of carbon dioxide by chemical means:

$$2NH_3 + 3O_2 = 2HNO_2 + 2H_2O$$
$$2HNO_2 + CaCO_3 = Ca(NO_2)_2 + H_2O + CO_2$$
$$Ca(NO_2)_2 + O_2 = Ca(NO_3)_2$$

132. Function of the carbon dioxide of the soil.—The solvent action of carbon dioxide is probably one of its most important functions in the soil. Constant biological activities, combined with the seasonal cropping influences, maintain this solvent and keep it continually in contact with the solution surfaces of the soil. Although a very weak acid when dissolved in water, its rapid formation and continuous action is productive of marked effects.

The availability of almost all of the plant nutrients is due either directly or indirectly to the action of carbon dioxide. Its influence on the potash of orthoclase, the phosphoric acid of tri-calcium phosphate and the calcium of calcium carbonate are well known examples:

$$2KAlSi_3O_8 + 2H_2O + CO_2 = H_4Al_2Si_2O_9 + 4SiO_2 + K_2CO_3$$
$$Ca_3(PO_4)_2 + 2H_2O + 2CO_2 = CaH_4(PO_4)_2 + 2CaCO_3$$
$$CaCO_3 + H_2O + CO_2 = CaH_2(CO_3)_2$$

Stocklasa[1] has correlated the carbon dioxide production

[1] Stoklasa, J., *Methoden zur Bestimmung der Atmungsintensität der Bakterien im Boden;* Zeit. f. d. Landw. Versuchswesen in Oesterreich, Band 14, Seite 1243-79, 1911.

with the quantity of phosphates found in the drainage water from certain soils. Some of his results are given in Table LV:

TABLE LV

Soil	P_2O_5 in Drainage Water (pounds to an acre)	Relative Production of CO_2 (milligrams to a pound of soil in 24 hours)
Loam	4.6	11
Clay	3.1	7
Lime soil	5.1	16
Organic soil	7.4	25

Stoklasa considers that the production of carbon dioxide is a measure of the intensity of bacterial action in the soil, and that in consequence of this activity the phosphorus is rendered soluble.

As far as biological activity is concerned, carbon dioxide seems to be a factor only insofar as it dilutes the oxygen.[1] This seems to be especially true of those bacterial processes involved in the formation of nitrates. When it exists to the exclusion of the oxygen, it produces anaërobic conditions but in this respect it functions in exactly the same way as does nitrogen or any other inert gas. Physiologically it seems to have no detrimental effects. Carbon dioxide increases so markedly with an increase in nitrate production that its presence can not be depressing.[2]

133. Importance of oxygen in the soil air.—Oxygen is the all-important gas of the soil air. Without it no weather-

[1] Plummer, J. K., *Some Effects of Oxygen and Carbon Dioxide on Nitrification and Ammonification in Soils;* Cornell Agr. Exp. Sta., Bul. 384, Dec. 1916.

Also, Owen, W. L., *Effect of Carbonates upon Nitrification;* Ga. Agr. Exp. Sta., Bul. 81, 1908.

[2] Neller, J. R., *Studies in the Correlation Between the Production of Carbon Dioxide and the Accumulation of Ammonia by Soil Organisms;* Soil Sci., Vol. V, pp. 225-241, 1918.

Stoklasa, Julius, *Methoden zur biochemischen Untersuchung des Bodens;* Handb. Biochem. Arbeitsmeth., Bd. 5, S. 843-910, 1912.

ing would occur, no minerals would break down, and no solution would be possible. Oxidation must go on rapidly and continuously in the normal soil, not only for chemical but for biological reasons as well. By it the organic matter that would soon accumulate to the exclusion of higher plant life is disposed of, and its nutrient materials are brought into a condition in which they may be absorbed by roots. The presence of oxygen is essential either directly or indirectly to the organisms that facilitate decomposition. Through such a process, roots of past crops, as well as other organic matter that has been plowed under, are rapidly changed in the soil. The processes of decay give rise to products, chiefly carbon dioxide, that are solvents of mineral matter, and leave the nitrogen and ash constituents more or less available for plant use.

Oxygen is also necessary for the germination of seeds and the growth of roots. These phenomena, although not involving the removal of large quantities of oxygen, are entirely dependent on its presence in considerable amounts.

134. Volume of the soil air.—The amount of air in soils is determined by their physical properties, the variability in any particular soil being due to certain changes to which such a soil is normally subject from time to time. The factors that influence the volume of air in soil are: (1) texture; (2) structure; (3) organic matter; and (4) moisture content.

It is a well recognized fact that the finer the texture, the better the granulation and the larger the amount of organic matter, the greater is the amount of pore space. Since about the same proportion of the pore space is filled with water in every soil when it is in optimum condition for crop growth, it is obvious that with finer texture, better granulation and increased organic matter, there will be a greater amount of air present.

Russell, E. J., and Appleyard, A., *The Influence of Soil Conditions on the Decomposition of Organic Matter in the Soil;* Jour. Agr. Sci., Vol. VIII, Part 3, pp. 385-417, 1917.

It must also follow that the larger the proportion of the interstitial space filled with water, the smaller will be the quantity of air contained. This does not mean that the soil with the higher percentage of water will contain the least air. The percentage pore space, which is determined by the texture, structure, and organic matter is a consideration also. These three factors, together with moisture content, are involved in the following formula for calculating air space:

$$\% \text{ Air Space} = \% \text{ Pore Space} - (\%H_2O \times \text{Vol. Wt.})$$

If one soil, containing 30 per cent. of water, has a pore space of 50 per cent. and a volume weight of 1.3, its air space would be 11 per cent. of the total soil volume. Another soil with 20 per cent. of moisture, a pore space of 40 per cent. and a volume weight of 1.6 would, on the other hand, contain only 8 per cent. of air. The above formula, however, is irremediably inaccurate in two respects. It does not allow for the air dissolved in the soil-moisture nor does it compensate for the influence of the gelatinous colloidal material that exists in the interstices especially of a heavy soil.

135. Movement of soil air.—There seems to be a slow but constant movement of air through the interstitial spaces of a normal soil in an attempt to create a homogeneous composition within the soil as well as to establish equilibrium with the atmospheric air. The major controls of such movement are (1) moisture and (2) temperature changes. The minor influences are (1) diffusion and (2) fluctuations in atmospheric pressure.

As water, when present in a soil, occupies certain of the interstitial spaces, it decreases the air space when it enters the soil and increases it when it leaves. The downward movement of rain-water produces a movement of soil air by forcing it out through the drainage channels below, while at the same time a fresh supply of air is drawn in behind the wave of saturation as the water passes down from the surface. The

movement thus occasioned extends to a depth where the soil becomes permanently saturated with water. Twenty-five per cent. of the air in a soil may be driven out by normal change in moisture content. Capillary movement, whether it be produced by evaporation, plant action or other normal forces, likewise produces movement of the soil air. In fact, every readjustment of soil-moisture, however slight, will produce a corresponding adjustment of the air films.

It is generally considered that the effect of normal temperature change on the contraction or expansion of the soil air is so slight as to produce but little movement. Ramann says,[1] "Since the coefficient of expansion of gas is only 1/273 to a degree Centigrade and since the temperature fluctuations to the depths of from four to eight inches are small, the diurnal exchange of gas is consequently slight." Bouyoucos,[2] by raising the temperature of both dry and moist soil held in a properly controlled apparatus, was able to measure the amount of air actually expelled. He found in every case that the gases driven off markedly exceeded the theoretical amounts.

TABLE LVI

EFFECT OF TEMPERATURE ON THE AMOUNT OF AIR EXPELLED FROM MOIST SOILS

Soil	Per Cent Moisture	Per Cent Porosity	Cubic Centimeters of Air Expelled From One-half Cubic Foot of Soil				Theoretical Increase for Each 10°C
			0-10°C	10°-20°C	20°-30°C	30°-40°C	
Sandy loam	11.0	48.2	289	354	382	419	250
Silt loam..	18.6	47.0	326	335	428	465	244
Clay.....	25.3	50.3	363	382	428	503	261
Peat.....	92.0	38.6	466	512	559	657	200

[1] Ramann, E., *Bodenkunde,* Seite 386; Berlin, 1905.

[2] Bouyoucos, G. J., *Effect of Temperature on Some of the Most Important Physical Processes in Soils;* Mich. Agr. Exp. Sta., Tech. Bul. 22, pp. 50-62, 1915.

Not only are the amounts of air expelled larger than the theoretical figures, but the differences rise with the temperature. With a change of 40° C. it is to be expected that the actual gas expelled will exceed the theoretical from 1.2 to 2.7 times, depending on the soil and its condition. This apparent discrepancy is due to the expansion of the aqueous vapor in the soil air and to the liberation of absorbed gases with a rise in temperature.

Diurnal fluctuations in temperature often rise as high as 15° C. for the upper six inches of soil in the summer months.[1] When it is remembered that monthly and seasonal differences are even greater than the diurnal and that this respiring effect continues day after day, the importance of temperature in relation to air movement cannot be minimized. If a six-inch layer of soil is raised from 5° C. to 20° C. in temperature, about 10 per cent. of its atmosphere will be expelled, providing the actual expansion is twice the theoretical.

The wide difference in the compositions of soil and atmospheric gases give rise to diffusion movements, especially of the oxygen and carbon dioxide. This tendency towards equilibrium is also important in the readjustments within the soil. As oxidation and carbon dioxide production do not occur equally in all parts of the soil, diffussion movements might easily be induced. The readjustments and equalizations between the soil air proper and that absorbed by the soil-moisture are probably largely diffusive. Although diffusion phenomena are slow, Buckingham[2] considers them quite important.

Waves of high or low atmospheric pressure, frequently involving a change of 0.5 inch on the mercury gauge, are constantly following each other eastward across the continent. Low pressure allows the soil air to expand and issue from

[1] See Swezey, G. D., *Soil Temperature at Lincoln, Nebraska;* Nebr. Agr. Exp. Sta., 16th Ann. Rep., pp. 95-102, 1903.

[2] Buckingham, E., *Contributions to Our Knowledge of Aëration of Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 25, 1904.

the soil, while a high pressure following causes the outside air to enter. An appreciable, but not important, movement of soil air is produced in this way. Gusts of wind, by affecting the air pressure, would function in the same way but presumably would influence only the superficial air spaces.

136. Practical modification of soil air.—The ordinary operations of tillage greatly influence the ventilation of the soil. When a soil is plowed, the bottom of the furrow is exposed directly to the air, and, by the separation of adhering particles and aggregates of particles, air is brought into contact with portions that previously have been shut off from atmospheric influence. It is partly because of its effect on soil ventilation that plowing is beneficial. The necessity for its practice is obviously greater in a humid region and on a heavy soil than in a region of light rainfall and on a light soil. The practice of listing corn in semi-arid regions, by which the soil is sometimes left unplowed for a number of years, would fail utterly on the heavy soils of a humid region.

Subsoiling, by loosening the subsoil, increases the ventilation at the lower depths. Rolling and subsurface packing both diminish the volume and the movement of air. Their essential difference is in their effect on moisture rather than on air. Harrowing and cultivation have the opposite effect, and both may under certain conditions increase the production of nitrates in the soil by promoting aëration.

Farm manures, lime, and other amendments that improve the structure of the soil have for that reason a beneficial action on soil aëration. By their effect on the physical condition of the soil, they increase its permeability, and by stimulating oxidation and carbon dioxide production they induce diffusion.

Under-drainage, by lowering the water-table and removing the soil-water from the larger capillary spaces, markedly influences the aëration of the soil and thus profoundly modifies the chemical and biological activities therein. There is a

very considerable movement of air in and out of tile drains, which cannot fail to influence the aëration of the soil above. The influence of irrigation on the soil is much like that of rainfall. The alternate filling and emptying of the interstitial spaces with water causes a very considerable change of air.

The roots of plants left in a soil after the crop has been harvested decay and leave channels in the soil through which air penetrates. Below the furrow slice, where the soil is not stirred and where it is usually more dense than at the surface, this affords an important means of aëration. The absorption of moisture from the soil by roots also causes the air to penetrate, in order to replace the water withdrawn.

137. Resume.—The air of the soil differs from the atmospheric air in being relatively lower in oxygen and comparatively very much higher in carbon dioxide. It is generally saturated with water-vapor. The percentage of nitrogen and other gases is about the same as in the atmosphere. The major portion of the soil atmosphere exists in the larger interstices. Its movement in most cases is due to moisture and temperature changes, although diffusion and fluctuations in barometric pressure are of some importance. A minor portion of the soil air is dissolved in the soil-water, the absorptive influences of the soil complexes probably playing a part also. Carbon dioxide is the predominating gas in the minor portion, which maintains an equilibrium with the more active soil air largely by diffusion.

While the amount of air in the soil varies with the texture, structure, and organic matter, the moisture content seems to be the dominant factor with volume as well as with movement. Although plowing, tillage, and manuring profoundly influence the soil air and its relationships to normal chemical and biological reactions, natural forces and processes, once the crop is on the soil, seem to control aëration.

CHAPTER XIII

THE ABSORPTIVE PROPERTIES OF SOILS[1]

It has been known from very early times that soils were able to take up and tenaciously hold such materials as salts and dyes. Aristotle, for example, noticed that sea water was purified when passed through sand. This capacity of soil to absorb and fix, more or less completely, materials added to it is called *absorption.* The earliest quantitative experiments were made by H. S. Thompson in England. He found that the soil was able to absorb considerable quantities of ammonia from ammonium sulfate, the acid radical being liberated. The importance of absorption phenomena has since attracted much attention, both from the practical and the theoretical standpoint.[2]

138. Types of absorption.—Two general types of absorption are usually recognized, physical[3] and chemical. In the former case the absorbed material is supposed to be concentrated on the surfaces of the absorbing substance, no chemical reaction taking place. The absorptive capacity of charcoal and cotton for dyes is a good example of such a phenomenon. In many cases, however, absorption is due to chemical reac-

[1] The literature on absorption by soils is so complicated and contradictory that only those concepts which are more or less definitely established and which have a practical bearing on soil management will be considered.

[2] A good review of literature will be found as follows:

Patten, H. E., and Waggaman, W. H., *Absorption by Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 52, 1908.

Prescott, J. A., *The Phenomenon of Absorption in its Relation to Soils;* Jour. Agr. Sci., Vol. VIII, No. 1, pp. 111-130, Sept., 1916.

[3] Physical absorption is sometimes spoken of as *adsorption.* The tendency at present is toward the elimination of this term.

tion. The tenacity with which soils absorb and hold phosphoric acid is probably due to the change that the soluble form undergoes almost immediately in the soil,[1] producing the sparingly soluble tri-calcium phosphate ($Ca_3(PO_4)_2$) or the practically insoluble iron and aluminum phosphates ($FePO_4$ and $AlPO_4$).

While it is generally considered that most of the material absorbed by soil, whether the action is chemical or physical, is concentrated at the surfaces of the solid material, there is some evidence that part of it penetrates, forming a solid solution. For example, the longer a gas is held at high pressure within an absorbing material, the less will be released when the pressure is lowered. Again, while most absorption is almost instantaneous, the final equilibrium is very slow. Such phenomena have given rise to a theory of molecular invasion.

In the soil it is impossible to know whether the absorption of any material has been purely physical, purely chemical, or due to both actions. In all probability both types of fixation occur. When a potassium compound is added to a soil, the potassium is taken up very readily. The fixation at first is probably physical. This type of absorption generates chemical reactions catalytically and the remainder, and possibly the greater proportion of the fixation, is probably chemical in nature.

139. Causes of absorption.—Way[2] was the first to advance any definite explanation of absorption. After studying the absorptive capacity of double silicates of sodium and aluminum, he decided that the phenomenon was purely chem-

[1] $CaH_4(PO_4)_2 + 2CaH_2(CO_3)_2 = Ca_3(PO_4)_2 + 4H_2O + 4CO_2$
Soluble — Insoluble

[2] Way, J. T., *On the Power of Soils to Absorb Manure;* Jour. Roy. Agr. Soc., England, Vol. 11, pp. 313-379, 1850. Also, *On the Power of Soils to Absorb Manure;* Jour. Roy. Agr. Soc., England, Vol. 13, pp. 123-143, 1852. Also, *On the Influence of Lime on the "Absorptive Properties" of Soils;* Jour. Roy. Agr. Soc., England, Vol. 15, pp. 491-515, 1854.

ical. Warington [1] also believed in the chemical hypothesis. Liebig, however, regarded absorption as largely physical. Van Bammelen [2] was the first to direct attention to the importance of both organic and inorganic colloidal matter to absorption phenomena. This type of explanation seems the most plausible in light of present knowledge of the colloidal state of certain soil constituents and from the fact that a soil very often does not remove different bases in chemically equivalent amounts.[3] The fact that a soil apparently saturated with one base is able to absorb quantities of another is additional argument against a purely chemical explanation.

In the soil, especially if it is of a clayey nature, there always exist certain quantities of hydrated aluminum silicates of indefinite chemical constitution. They are generally colloidal in nature.[4] Such materials, as well as those of an organic character, possess high absorptive capacities, not only because of their tremendous surface exposures but also because of their tendency to react quickly and easily with substances in the soil solution. According to Van Bemmelen, who made

[1] Warington, R., *On the Part Taken by Oxide of Iron and Alumina in Absorptive Action of Soils;* Jour. Chem. Soc., (London), Vol. 6, pp. 1-19, 1868.

[2] Van Bemmelen, J. M., *Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde;* Landw. Vers. Stat., Band 35, Seite 75, 1888. Also, *Die Absorption,* Dresden, 1910.

[3] The uncertainty regarding the real explanation of absorption is shown by the controversy of Weigner, who holds to the colloidal theory, with Gans, who believes the phenomenon is chemical.

Weigner, G., *The Chemical or Physical Nature of Colloidal Aluminum Silicates Containing Water;* Centrbl. f. Min. u. Paläontol., No. 9, pp. 262-272, 1914.

Gans, R., *Concerning the Chemical or Physical Nature of Colloidal Water-containing Aluminum Silicates;* Centrbl. f. Min. u. Paläontol., No. 22, pp. 699-712; No. 23, pp. 728-741, 1914.

[4] The absorptive capacity of the soil is often ascribed to zeolites. The presence of zeolites in the soil, however, is extremely improbable. Water and the absence of oxidizing agents are essential for their formation. They are products of hydrometamorphism and not of weathering. It seems probable that the processes of weathering are not only opposed to zeolite formation but would destroy those already present.

Merrill, G. P., *Weathering of Micaceous Gneiss;* Bul. Geol. Soc. Amer., Vol. 8, pp. 162-166, 1879.

a very exhaustive study of the subject, the following colloidal materials may function in the soil:

1. Partially decayed remains of plant and animal tissue.
2. Colloidal iron, aluminum, and silica.
3. Colloidal silicates formed through weathering.

Van Bemmelen also credits crystalline silicates with some absorptive power, but he does not consider such action particularly important.

The combinations produced by absorption are often weak, it being possible to leach out the substances held in the water of the colloidal gels. The following example of one kind of absorption is given by Van Bemmelen [1] and shows how complex the phenomenon may become: ten grams of a hydrogel having the composition $SiO_2.4.2\,H_2O$, shaken with 100 cubic centimenter solution of 20 molecular equivalent KCl, absorbed 0.8 to 1.1 molecular equivalent of the dissolved substance. The absorption in this case was as if the solution had been diluted with 4.2 to 5.8 centimeters of water. As the amount of gel water in 10 grams of hydrogel of SiO_2 is about 5 cubic centimeters, the assumption may be made that the dissolved substance is taken up in equal concentration by the gel water. Ten grams of hydrogel of SiO_2 shaken with 100 cubic centimeter solution of 50 molecular equivalent KCl—that is, two and a half times the concentration of the former solution—absorbs two and a half times as much, or 2.1 to 2.5 molecular equivalent. This applies also to concentrations five times stronger than the first mentioned above, but beyond that the relation is not so simple. It serves, however, to illustrate the manner in which the absorption takes place from dilute solutions.

140. The absorptive capacity of soils.[2]—The absorptive

[1] Van Bemmelen, J. M., *Die Absorptionsverbindungen und das Absorptionsvermögen der Ackererde;* Landw. Vers. Stat., Band 35, Seite 75, 1888.

[2] A few important citations are as follows:

Peters, E., *Ueber die Absorption von Kali durch Ackererde;* Landw. Ver. Stat., Bd. 2, Seite 113-151, 1860.

capacity of any particular soil for gases, water, or salts in solution, under any particular condition, depends on the texture of the soil and on the time during which the action is allowed to continue. The absorptive power of a soil may be determined by percolating a solution of known strength through a column of the soil or by shaking the sample with a definite amount of the solution. The following data from Parker [1] were obtained by shaking a 35-gram portion of soil for two days with a solution carrying the equivalent of about 6.5 grams of KCl:

TABLE LVII

EFFECT OF TEXTURE ON THE ABSORPTION OF POTASSIUM.

SOIL TYPE	POTASSIUM ABSORBED EXPRESSED AS MILLIGRAMS OF KCl.
Cecil clay	325
Decatur clay loam	240
Carrington loam	225
Norfolk sandy loam	148

Sullivan, E. C., *The Interaction Between Minerals and Water Solutions;* U. S. Geol. Survey, Bul. 312, 1907.

Morse, F. W., and Curry, B. E., *Reactions Between Manurial Salts and Clay, Mucks and Soils;* N. H. Agr. Exp. Sta., 29th Ann. Rep., pp. 271-293, 1908.

Demolon, A., and Bronet, G., *Sur la Pénétration des Engrais Solubles dans les Sols;* Ann. Agron., Tome 28, pp. 401-418, 1911.

Bogue, R. H., *Absorption of Potassium and Phosphorus Ions by Typical Soils;* Jour. Phys. Chem., Vol. 19, No. 8, pp. 665-695, 1915.

McCall, A. G., Hildebrandt, F. M., and Johnston, E. S., *The Absorption of Potassium by the Soil;* Jour. Phys. Chem., Vol. 20, No. 1, pp. 51-63, 1916.

McBeth, J. G., *Fixation of Ammonia in Soils;* Jour. Agr. Res., Vol. IX, No. 5, pp. 141-155, 1917.

Wyckoff, M. I., *Absorption of Ammonium Sulfate by Soils and Quartz Sand;* Soil Sci., Vol. III, No. 6, pp. 561-564, 1917.

Kelley, W. P., and Cummins, A. B., *Chemical Effect of Salts on Soils;* Soil Sci., Vol. XI, No. 2, pp. 139-159, Feb., 1921.

[1] Parker, E. G., *Selective Absorption by Soils;* Jour. Agr. Res., Vol. 1, No. 5, pp. 179-188, Dec., 1913.

It is noticeable that the absorption increases with the fineness of the texture, indicating that the heavier the soil, the greater is the amount of material present that possesses marked capacity for fixation. Organic matter, in general, does not seem as efficacious as mineral material in absorptive reactions, especially those involving salts.

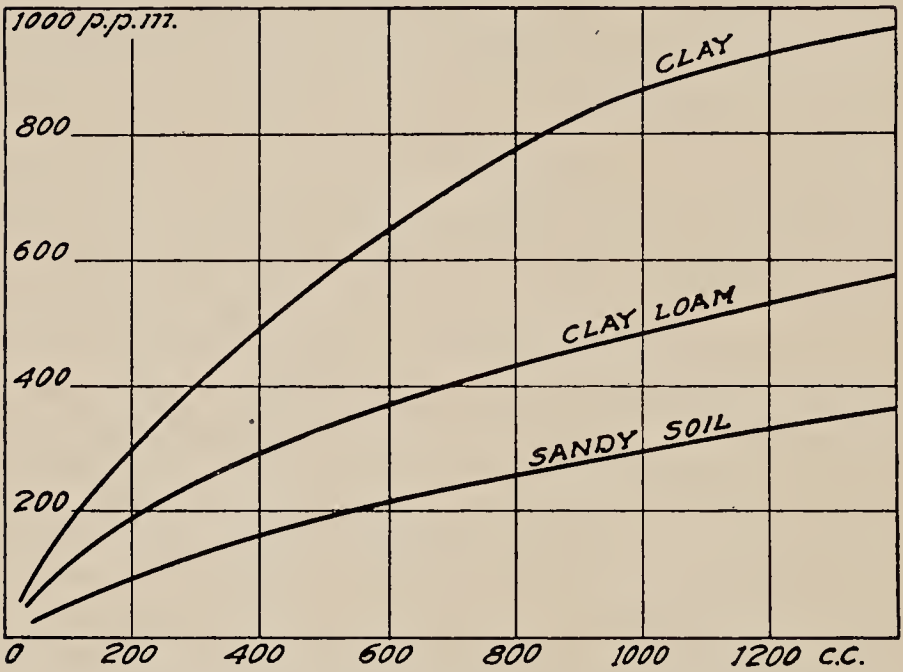


FIG. 49.—Curves showing the absorption of K in parts per million by various soils from a solution containing 200 parts to the million of K. The volume of the percolate is used as the abscissas.

The influence of time on absorption is shown by the following data from Schreiner and Failyer.[1] In this case 100 gram portions of soil were treated with 500 c.c. of a mono-calcium phosphate solution carrying 100 parts per million of PO_4. The

[1] Schreiner, O., and Failyer, G. H., *The Absorption of Phosphates and Potassium by Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 32, p. 9, 1906.

parts per million of PO_4 absorbed after certain intervals of time are given below. (See also Fig. 49) : [1]

TABLE LVIII

EFFECT OF TIME AND TEXTURE ON THE ABSORPTION OF PO_4 FROM A SOLUTION OF $CaH_4(PO_4)_2$.

TIME	PO_4 ABSORBED IN PARTS PER MILLION	
	CLAYEY SOIL	FINE SANDY SOIL
3 minutes	400	235
40 minutes	410	255
1 hour	415	260
2 hours	435	315
4 hours	440	335
24 hours	445	370

It must not be inferred that, when a solution is brought in contact with a soil, it always becomes weaker because of absorption. Negative absorption may occur in which the solvent is taken up more rapidly than the solute. Concentration is thus induced.

141. Selective absorption.[2]—The fixation phenomena by the soil, whether physical or chemical, is of two types: (1) the absorption of molecules, the compound being taken up unchanged; and (2) the absorption of ions. In the first case,

[1] The law which appears to govern absorption of phosphates and potash by the soil may be expressed mathematically as follows:

$$\frac{dy}{dv} = K\,(A - Y)$$

in which K is a constant, A the maximum quantity possible for the soil to absorb and y the quantity actually fixed when v, volume of the solution, has percolated through. A short discussion of the mathematics of this law may be found in the following publication: Schreiner, O., and Failyer, G. H., *The Absorption of Phosphates and Potassium by Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 32, pp. 23-24, 37-39, 1906.

[2] A very good discussion of selective absorption is found in the following: Parker, E. G., *Selective Absorption by Soils;* Jour. Agr. Res., Vol. 1, No. 5, pp. 179-188, 1913.

if a residue is left, it is unchanged except in concentration. Such would be the case in the absorption of certain dyes, of gases and of hydroxides of various kinds, where the molecule is fixed intact. This first form of absorption is by no means as important as the selective absorption of ions.

Certain compounds, called electrolytes,[1] tend when in solution to ionize or split up into ions. Thus potassium nitrate, a neutral salt, breaks up into K^+ and NO^-_3 ions, the degree of ionization depending on the concentration of the solution. When such a solution is brought into contact with soil, the latter usually, but not always, exerts a greater affinity for the basic ion, leaving an excess of the acid radical in solution. The water present furnishes small amounts of H^+ and OH^- ions, thereby encouraging the formation of KOH, which is absorbed intact, together with the K^+ and OH^- ions. This action, therefore, leaves the H^+ and NO^-_3 ions preponderant in the solution, which is of necessity acid in reaction due to the hydrogen ion concentration. This selective absorption may be demonstrated with any neutral salt and any neutral absorbent, the resultant extract always being acid due to the selective absorption of the basic ions.

142. Substitution of bases.[2]—Associated with the selective absorption of bases from solution there is a liberation of

[1] According to the theory of the electrolytic-dissociation or ionization, many compounds under certain conditions break up into electrically charged portions called ions. Ions may be single atoms or a group of atoms. Many inorganic substances are almost completely ionized. A few organic compounds exhibit marked dissociation but many are not appreciably affected.

Water dissociates into H^+ and OH^- ions to the extent of about .00001 of a per cent. or 1 part in 10,000,000. An acid yields hydrogen ions and other ions carrying the remainder of the molecules. Alkalies give hydroxyl ions and other ions consisting of the remaining portion of the molecules. The acidity or alkalinity of a solution is determined by its hydrogen-ion concentration.

[2] Van Bemmelen, J. M., *Das Absorptionsvermögen der Ackererde;* Landw. Vers. Stat., Band 21, Seite 135-191, 1877.

Sullivan, E. C., *The Interaction between Minerals and Water Solutions;* U. S. Geol. Survey, Bul. 312, 1907.

Wiegner, G., *Zum Basenaustausch in der Ackererde;* Jour. Landw., Band 60, Seite 111-150, 197-222, 1912.

other bases from the soil, which appear in the filtrate as ions and in combination with acid radicals. Such phenomena may be considered as mere basic exchange, pushed forward by the mass action of the ion absorbed, and is called *substitution of bases.* The change may be illustrated as follows:

$$KCl + X_n \text{ Silicate} \rightleftarrows X_nCl + K \text{ Silicate}$$

It is unlikely that this reaction actually takes place to any extent in fertilizer practice.[1] It is more probable that the acid produced by the selective absorption liberates the bases from their loose union with the hydrated aluminum silicate complexes.

$$HCl + X_n \text{ Silicates} \rightleftarrows X_nCl + H \text{ Silicates}$$

A dilute solution of potassium chloride filtered through a soil will produce a filtrate containing some calcium, magnesium, or chloride or all of these salts and some potassium chloride. The more dilute the solution, the larger will be the proportion retained, but the less the total quantity absorbed. Peters [2] treated 100 grams of soil with 250 cubic centimeters of a solution of potassium salts, and found that the potassium of separate salts was retained in different proportions, and that the more concentrated solutions lost relatively less than the weaker ones, although more actual potassium was removed from the former.

TABLE LIX

SOLUTION	GRAMS OF K_2O ABSORBED FROM A 1/10 NORMAL SOLUTION	GRAMS OF K_2O ABSORBED FROM A 1/20 NORMAL SOLUTION
KCl	.3124	.1990
K_2SO_4	.3362	.2098
K_2CO_3	.5747	.3134

[1] Parker, E. G., *Selective Absorption by Soils;* Jour. Agr. Res., Vol. 1, No. 5, p. 180, 1913.

[2] Peters, E., *Über die Absorption von Kali durch Ackererde;* Landw. Vers. Stat., Band 2, Seite 113-151, 1860.

The same bases are not always absorbed in the same proportion by different soils; one soil may have a greater absorptive power for potassium, while another may retain relatively more ammonia. They seem to be somewhat interchangeable, as any absorbed base may be released by a number of others in solution. The absorptive power of a soil for certain bases is reflected in the composition of the drainage water from the soil. The latter varies with the soil, and a soluble fertilizer applied to one soil will have a different effect on the composition of drainage water than if applied to another soil. This is well illustrated from lysimeter experiments by Gerlach [1] at Bromberg. Several soils were used, a portion of each being fertilized and unfertilized respectively. The lysimeters were 1.2 meters deep and contained 4 cubic meters of soil. The drainage water was collected and analyzed for four years. The first year there was no crop, the second year potatoes were grown, the third oats, and the fourth rye. The following results were obtained:

TABLE LX

AVERAGE COMPOSITION OF DRAINAGE WATER IN PARTS PER MILLION. BROMBERG.

SOIL	TREATMENT	TOTAL N	NO_3	ORGANIC N	K_2O	CaO
Moor soil.....	Fertilized	32.7	30.0	2.7	32.2	405
	Untreated	65.0	60.3	4.7	26.2	507
Sand low in organic matter...	Fertilized	25.5	25.1	.4	25.1	92
	Untreated	20.9	20.4	.5	8.5	90
Sandy loam high in organic matter.....	Fertilized	67.8	64.6	3.1	70.2	399
	Untreated	69.5	66.1	3.4	47.4	414

[1] Gerlach, U., *Über die durch Sickerwasser dem Boden Entzogenen Menge Wasser und Nahrstoffe;* Ill. Landw. Zeitung, 30 Jahrgrange, Heft 95, Seite 871-881, 1910.

143. Importance of absorption.—Absorption is important, not only because it allows the soil to retain certain nutrients against excessive leaching, but because it facilitates the condensation and concentration of gases within the soil.[1] Russell and Appleyard[2] have shown that the inner soil air is held very tightly and must in consequence be under considerable pressure. Such gas absorption tends to force reactions which otherwise would be very slow. A part of the catalytic power of the soil may be accounted for in this way. Moreover, the absorption of water by the soil is by no means unimportant. It is because of such phenomena that the moisture of the soil occurs in various forms and possesses distinctly different relationships to the plant.

The selective absorption of the basic ions by soils of every type is important in a number of ways. In the first place, potassium, calcium, magnesium, and iron function in the soil as bases. Selective absorption tends to conserve these nutrients to the exclusion of their acid radicals, which are readily lost in drainage. Phosphorus, however, has a different status, for although it is held as a part of an acid radical (PO_4), it is saved from leaching by the insolubility of the compounds which tend to form. In the second place, selective absorption apparently produces residues when fertilizers are added and these residues are almost always acid. Sodium nitrate, ammonium sulphate, potassium chloride, and potassium sulphate will leave an acid residue in the soil solution unless influenced by extraneous factors, such as the addition of lime or the action of plants.

[1] Patten, H. E., and Gallagher, F. E., *Absorption of Vapors and Gases by Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 51, 1908.

McGeorge, W., *Absorption of Fertilizer Salts by Hawaiian Soils;* Haw. Agr. Exp. Sta., Bul. 35, p. 32, 1914.

Cook, R. C., *Factors Affecting the Absorption and Distribution of Ammonia Applied to Soils;* Soil Sci., Vol. II, No. 4, pp. 305-344, 1916.

[2] Russell, E. J., and Appleyard, A., *The Atmosphere of the Soil: Its Composition and the Causes of Variation;* Jour. Agr. Sci., Vol. VII, Part 1, pp. 1-48, 1915.

The acidity of soils, which is a function not only of the soil solution but of the solid portions also, is frequently attributed to certain absorptive phenomena, one idea being that, due to physical and chemical absorption of bases, a concentration of the hydrogen ion is produced and actual acidity results. Basic exchange seems to liberate iron and aluminum, the salts of which easily hydrolize and yield acid solutions. If, as some investigators maintain, the toxic principle of the so-called acid soils is active aluminum, manganese or similar elements, absorption may again be the activating phenomenon, since an unsatisfied absorptive capacity, especially for calcium and magnesium, seems to favor the presence of such constituents in the soil solution.

The absorptive power of the soil is a controlling factor as far as the composition and concentration of the soil solution is concerned. Any study of the dynamic relationships of the water solution that exists in the soil interstices and in the colloidal complexes which coat the soil particles, must reckon with absorption phenomena and all of the factors which tend to influence them.

CHAPTER XIV

THE SOIL SOLUTION

The soil is a heterogeneous mixture of solids, gases, and a liquid. The mineral constituents come from the debris of rock, the organic matter is derived from plant and animal tissue, while through and around these complex materials the water and gases of the soil circulate in ever-changing proportions. Minute organisms are also present in great numbers, aiding, through their enzymic activities, the intricate transformations. As a result of the reactory inter-relations of the soil components, a solution is generated which tends to come into equilibrium with the solids and gases with which it is in contact. As it is from this source that plants obtain their mineral nutrients, the soil solution and its control demand especial attention.

The fundamental error of many soil conceptions has been to regard the soil as a static system. Chemical, physical, and biological activities are admitted, but they have been regarded as of little importance in influencing the soil mass as a whole. Such a conception is in error as every constituent of the soil is dynamic. The presence of large amounts of material in a colloidal state makes the constancy of any particular condition impossible over any extended period.

In studying the soil solution, especially as to its composition and concentration, the phenomenon of absorption can not be ignored. The tendency of certain portions of the soil to go into solution, while other parts are absorbing both the solvent and the solute, must be reckoned with. Moreover, the losses of nutrients to the plant and through leaching are

a factor to be considered. Obviously the concentration and composition of the soil solution is first of all a function of the absorptive capacity of the soil complexes, modified by the rate of solution and the magnitude of crop and leaching activities.

144. Absorption and the soil solution.—In a bare moist soil, where there is no evaporation or leaching to disturb equilibrium tendencies, the soil presents a three-phase system. The phases are: (1) the solution surfaces,[1] (2) the absorptive or colloidal surfaces, and (3) the

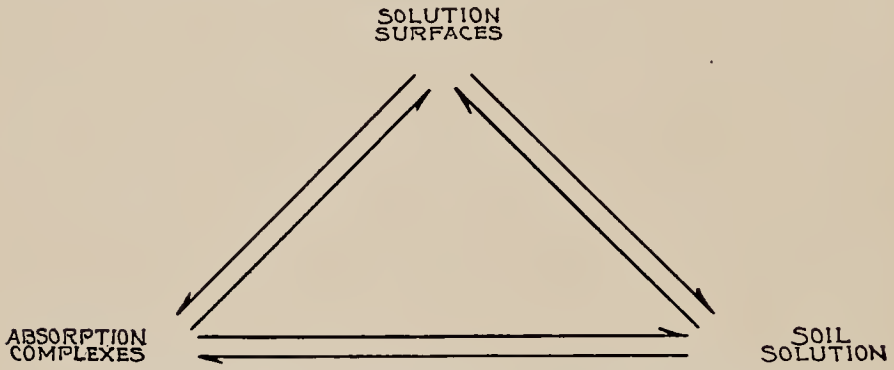


FIG. 50.—Diagram showing the equilibrium tendencies that exist between the solution surfaces, the colloidal complexes and the soil solution.

soil solution itself. When solution takes place, the constituents so affected are acquired in part by the soil moisture as a solute and in part by the absorptive complexes. There is a constant attempt at equilibrium, which of course is never attained as long as solution continues. Under field conditions, many other disturbing factors enter. The rate of solution may vary, and the capacity and character of the absorbing colloidal complexes are always changing. Moreover, the amount of water in the soil is never constant, due to drainage and evaporation. The feeding of the plant, as re-

[1] This term refers to the soil surfaces from which solution takes place.

gards both water and nutrients, and losses by leaching, must always be considered. In addition, the effect of tillage as well as the common practices of adding farm manure, plowing under of green-crops and applying fertilizers and lime, are constantly effective in obstructing equilibrium adjustments.[1] (See Fig. 50.)

The soil solution is, therefore, markedly dynamic in character, constantly changing in composition and concentration. Its important control is absorption, the absorptive surfaces acting as a depository, in which active reserve nutrients are held. As the solution is depleted in any constituent, quicker adjustment takes place between the solvent and the colloidal complexes than is possible between the solution and the solution surfaces. Rapid adjustments, as far as the supply of nutrients for plants is concerned, is possible only because of the absorptive properties of the colloidal complexes of the soil.

145. Methods of studying the soil solution.—Questions regarding the soil solution are difficult to answer because no adequate procedure has been devised for extracting a representative sample of the solution as it existed in the soil. Moreover, no wholly satisfactory method has been perfected for its measurement in place. Various extractive methods have been tried. Briggs and McLane[2] attempted to sample the solution by the use of a centrifuge developing a force of two or three thousand times that of gravitation. When the soil contained a rather large quantity of capillary water, a small amount of it could be removed in this way.

[1] Bouyoucos has shown that even under controlled conditions the equilibrium between finely ground minerals and water is not absolute or real due to the complex hydration and hydrolysis which continually occur. Bouyoucos, G. J., *Rate and Extent of Solubility of Minerals and Rocks under Different Treatments and Conditions;* Mich. Agr. Exp. Sta., Tech. Bul. 50, July, 921.

[2] Briggs, Lyman J., and McLane, John W., *The Moisture Equivalent of Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 45, pp. 6-8, 1907.

Another device, perfected by Briggs and McCall,[1] consists of a close-grained, unglazed porcelain tube, closed at one end and provided at the other with a tubulure, by which it can be connected with an exhausted receiver. This tube is moistened and buried in the soil. If the moisture content of the soil is sufficient to reduce the pressure of the capillary water surface in the soil to less than half the difference between the pressure inside and outside of the tube, there will be a movement of water inward. The water may be collected and analyzed.

More recently Van Suchtelen has used another method to obtain the soil solution.[2] He replaces the soil-water by means of paraffin in a liquid state, at the same time subjecting the soil on a filter to suction. The displaced water is considered to represent the soil solution. Later Van Suchtelen and Itano substituted pressure for suction, modifying the apparatus to meet the new procedure. This apparatus has been further perfected by Morgan.[3] Lipman[4] has proposed a method in which very high pressure, a minimum of 53,000 pounds to the square inch, is utilized in squeezing out the soil-water.[5]

All such methods are open to the objection that the sample is not representative. The soil solution changes both in con-

[1] Briggs, L. J., and McCall, A. G., *An Artificial Root for Inducing Capillary Movement of Soil Moisture;* Science, N. S., Vol. 20, pp. 566-569, 1904.

[2] Van Suchtelen, F. H. H., *Methode zur Gewinnung der Natürlichen Bodenlosung;* Jour. f. Landw., Band 60, Seite 369-370, 1912.

[3] Morgan, J. F., *The Soil Solution Obtained by the Oil Pressure Method;* Mich. Agr. Exp. Sta., Tech. Bul. 28, Oct., 1916.

[4] Lipman, C. B., *A New Method of Extracting the Soil Solution;* Univ. Cal. Pub., Agr. Sci., Vol. 3, No. 7, pp. 131-134, 1918. Ramann, E., *et al.*, have proposed a similar method but with less pressure. Internat. Mit. f. Bodenkunde, Bd. 6, Seite 27, 1916.

For a good criticism of this method, see Northrup, Zea, Science, N. S., Vol. XLVII, No. 1226, p. 638, June 1918.

[5] Ischerekov in 1907 used ethyl alcohol to displace the water in a soil column utilizing only the force of gravity. Parker claims that this method is of considerable value. He found that data so obtained compared closely with that obtained from the water extract method. Parker, F. W., *Methods of Studying the Concentration of the Soil Solution;* Soil Sci., Vol. XII, No. 3, pp. 209-232, 1921.

centration and composition so readily that the addition of extraneous material or the exertion of unnatural pressure defeat the object of the determination. Moreover, the soil solution is probably not homogeneous and unless practically all of it is removed a sample of value cannot be obtained. The significance of such a sample, if it were attained, is questionable, as it is impossible to know the proportion of the soluble nutrients that may actually be appropriated by the growing plant.

The method of obtaining soil extracts has been used to a greater extent than any other in studying the soil solution. Water is the usual solvent. The Bureau of Soils filter method [1] is commonly followed. As might be expected, it is purely arbitrary in its procedure, the idea being to make the results comparative rather than strictly quantitative. Soil and water in the proportions of 1 to 5 are mixed, stirred three minutes and allowed to stand twenty minutes. The supernatant liquid is then forced through a Pasteur-Chamberland filter and a clear extract obtained for analysis.

The solution obtained is not representative of the soil-water and its solutes. It is only an extract of the soil. The addition of a large amount of water is a disturbing factor. The concentration of the extract is also modified by the absorptive power of the soil, being relatively greater for a sandy than for a clayey soil. Moreover, the differential influence of the solvent comes into play, for as soon as solution begins, the solvent is no longer pure water but a solution of constantly changing efficiency. Nevertheless, the work of Hoagland, Stewart and Burd [2] indicates that there is not only a relation-

[1] Schreiner, O., and Failyer, G. H., *Colometric, Turbidity and Titration Methods Used in Soil Investigations;* U. S. Dept. Agr., Bur. Soils, Bul. 31, 1906.

[2] Hoagland, D. R., *The Freezing Point Method as an Index of Variations in the Soil Solution Due to Season and Crop Growth;* Jour. Agr. Res., Vol. XII, No. 6, pp. 369-395, 1918.

Stewart, G. R., *Effect of Season and Crop Growth in Modifying the Soil Solution;* Jour. Agr. Res., Vol. XII, No. 6, pp. 311-368, 1918.

ship between the water extract of a soil and its productivity, but a correlation with the strength of the soil solution as well. The extract method is especially valuable in studying the nitrates of the soil solution. As nitrate nitrogen does not suffer as much absorption as do the nutrient bases, that which appears in the extract is a fair measure of the strength of the soil solution insofar as this constituent is concerned.

The only method for measuring the concentration of the soil solution *in situ* is that of Bouyoucos.[1] This is known as the depression of the freezing point method. It is possible, when dealing with a pure solution of a known salt, to calculate its concentration by determining how much the freezing point is lowered or depressed below 0° C. This principle is applied to the soil by using a Beckman thermometer and the proper control apparatus. As the soil solution carries a great number of different ions in unknown proportions, it is impossible to calculate even the concentration with accuracy, a factor of somewhat doubtful validity being utilized. The procedure gives nothing regarding the presence of specific ions nor are its results uniform, due to the variable dissociation of the salts present. Nevertheless the method has thrown much light on the many difficult problems of the soil and its solution.

146. Qualitative composition of the soil solution.—Once the dynamic character of the soil solution is conceded, three points of importance immediately demand attention: (1) the qualitative composition of the soil solution and its concentration *in toto,* (2) the quantitative composition, and (3) the factors most important in influencing both the composition and the concentration of the solution.

It must be recognized at the outset that the soil solution

Burd, J. S., *Water Extractions of Soils as Criteria of their Crop Producing Power;* Jour. Agr. Res., Vol. XII, No. 6, pp. 297-309, 1918.

Hoagland, D. R., Martin, J. C., and Stewart, G. R., *Relation of the Soil Solution to the Soil Extract;* Jour. Agr. Res., Vol. XX, No. 5, pp. 381-395, 1920.

[1] Bouyoucos, G. J., *Further Studies on the Freezing Point Lowering of Soils;* Mich. Agr. Exp. Sta., Tech. Bul. 31, Nov., 1916.

is generally dilute except in arid regions under conditions of alkali. The concentration probably very seldom exceeds 30,000 parts per million and is normally very much lower. Moreover, the greater proportion of the solute is in an ionic state, molecules appearing only when the concentration is relatively high. It is well to note that the plant absorbs most of its nutrients in the ionic condition.

From the knowledge obtained by the analysis of soil extracts, it is safe to assume that all of the common bases and acid radicals normally occur in the soil solution. Thus, K^+, Na^+, Mg^{++}, Ca^{++}, Fe^{+++}, Al^{+++} and NH_4^+ ions may be expeeted as well as such ions as $SO_4^{=}$, $SiO_4^{\equiv}$, Cl^-, $PO_4^{\equiv}$, NO_3^-, NO_2^- and $CO_3^{=}$. Since water dissociates slightly, H^+ and OH^- ions will also be present. The reaction of the solution will depend on its hydrogen-ion concentration and may be alkaline, neutral or acid as the case may be. Most soil solutions seem to be slightly acid,[1] possibly due to the action of carbon dioxide.

Morgan [2] found on an examination of the solutions obtained from soils by the oil pressure method that, as the moisture increased, the concentration of the solution decreased. These findings are amply corroborated by the work of Bouyoucos [3] with the depression of the freezing point method. The latter presents data regarding the actual concentrations at various moisture contents, which seem to indicate the general differences that may be expected between soils of different types.

[1] Gillespie, L. J., *The Reaction of Soil and Measurements of Hydrogen-ion Concentration;* Jour. Wash. Acad. Sci., Vol. 6, No. 1, pp. 7-16, 1916.

Sharp, L. T., and Hoagland, D. R., *Acidity and Adsorption in Soils as Measured by the Hydrogen Electrode;* Jour. Agr. Res., Vol. VII, No. 3, pp. 123-145, 1916.

Hoagland, D. R., *Relation of the Concentration and Reaction of the Nutrient Medium to the Growth and Absorption of the Plant;* Jour. Agr. Res., Vol. XVIII, No. 2, pp. 73-117, 1919.

[2] Morgan, J. F., *The Soil Solution Obtained by the Oil Pressure Method;* Mich. Agr. Exp. Sta., Tech. Bul. 28, 1916.

[3] Bouyoucos, G. J., *Further Studies on the Freezing Point Lowering of Soils;* Mich. Agr. Exp. Sta., Tech. Bul. 31, pp. 14-15, 1916.

TABLE LXI

THE CONCENTRATION OF THE SOLUTION OF VARIOUS SOILS AS DETERMINED BY THE DEPRESSION OF THE FREEZING POINT. EXPRESSED IN PARTS PER MILLION BASED ON DRY SOIL.

Soil	Moisture %	Concentration P. P. M.	Moisture %	Concentration P. P. M.
Superior clay...	18.8	29,268	39.4	415
Miami silt loam.	8.8	19,560	36.0	707
Carrington loam	15.2	16,390	38.5	463
Plainfield sand.	5.0	6,342	24.6	366
Peat.....	61.3	23,333	208.5	2,222

147. Quantitative composition of the soil solution.— Data regarding the relative or actual quantities of the nutrient elements in the soil solution are not only very meagre but unreliable. Morgan [1] found, on comparing the solutions obtained from different soils by the oil pressure method, that the potassium (K) might vary from 4 to 180 parts per million based on dry soil; the phosphorus (PO_4) from .2 to 4.6, and the calcium (Ca) from 6 to 1000 parts per million. King,[2] in his extensive work with soil extracts, found the nitrate nitrogen (NO_3) extremely variable, ranging from a fraction of a part per million to more than 150 parts per million in the same soil at different times. A greater fluctuation is to be expected, however, in the nitrate nitrogen than with the other elements, since the presence of soluble nitrogen in the soil solution is due very largely to biological activity. The following figures from Morgan, although the different samples should not be compared, show what may be expected in general regarding the concentration of particular elements in the soil solution.

[1] Morgan, J. F., *The Soil Solution Obtained by the Oil Pressure Method;* Mich. Agr. Exp. Sta., Tech. Bul. 28, 1916.

[2] King, F. H., *Investigations in Soil Management;* U. S. Dept. Agr. Bur. Soils, Bul. 26, 1905.

TABLE LXII

THE AMOUNTS OF POTASSIUM, PHOSPHORUS, AND CALCIUM IN THE SOLUTION OF VARIOUS SOILS AS DETERMINED BY THE OIL PRESSURE METHOD. EXPRESSED IN PARTS PER MILLION BASED ON DRY SOIL.

Soils	Moisture Percentage	Parts Per Million			
		K	PO_4	Ca	$NH_3+NO_3+NO_2$
Fine sandy loam	29.7	7.18	1.54	9.10	.91
Medium sandy loam	27.2	9.82	1.41	12.75	13.56
Clyde fine sandy loam	41.9	12.44	1.85	37.12	3.80
Miami silt loam	37.8	27.02	4.64	25.93	1.20
Miami clay	24.5	11.03	1.13	10.56	1.61
Peat	132.9	139.33	2.19	213.70	33.91

Morgan's data indicate that the least variation may be expected in the phosphorus (PO_4) content, which does not differ greatly in different soil solutions nor does it vary to any great extent in the same soil. Potassium (K) and especially calcium (Ca) show considerable fluctuation, as does the nitrate nitrogen (NO_3), as has already been emphasized. The figures of Morgan correlate fairly well with the data obtained by the Bureau of Soils [1] by means of centrifugal extraction. The potassium (K) averaged about 28 parts per million based on the solution, the calcium (Ca) 32, and the phosphorus (PO_4) 8 parts per million.

148. Influence of season and crop on the soil solution.— It has already been emphasized that the concentration and the composition of the soil solution suffer wide fluctuations. The principal causes of such variations are as interesting as

[1] Cameron, F. K., *The Soil Solution;* p. 40, Easton, Pa., 1911.

they are important since they have a bearing not only on the chemical and biological phenomena within the soil but also on its plant relationships.

The broadest and most general factors affecting the soil solution are season and crop. Whether the soil is fallow or covered with vegetation, a great seasonal influence is evident on the soil and its solution. Stewart,[1] working in California with extracts from thirteen soils held in large containers, found notable fluctuations of nitrates, calcium, potassium, and magnesium both in bare and cropped earth. The phosphates did not show great variation. The soluble nutrients were markedly higher in the bare soils, the differences between the various types being quite noteworthy. The good soils seemed to have the more concentrated soil solution, a conclusion already reached by a number of investigators.[2] When crops were growing on these soils, the concentration of soluble nutrients not only was lower than with the fallowed areas, but it was about the same in every type of soil. The inherent solution capacity of the different soils was roughly indicated by the crop growth. Hoagland's [3] study of the concentration

[1] Stewart, G. R., *Effect of Season and Crop Growth in Modifying the Soil Solution;* Jour. Agr. Res., Vol. XII, No. 6, pp. 311-368, 1918.

[2] Snyder, H., *The Water-Soluble Plant Food of Soils;* Science, N. S., Vol. 19, No. 491, pp. 834-835, 1904.

King, F. H., *Investigations in Soil Management;* Madison, Wis., 1904.

King, F. H., *Investigations in Soil Management;* U. S. Dept. Agr., Bur. Soils, Bul. 26, 1905.

Mitscherlich, E. A., *Eine Chemische Bodenanalyse für Pflanzenphysiologische Forschungen;* Landw. Jahrb., Bd. 36, Heft 2, S. 309-369, 1907.

Lyon, T. L., and Bizzell, J. A., *The Plant as an Indicator of the Relative Density of the Soil Solutions;* Proc. Amer. Soc. Agron., Vol. IV, pp. 35-49, 1912.

Hall, A. D., Brenchley, W. E., and Underwood, T. M., *The Soil Solution and the Mineral Constituents of the Soil;* Philosoph. Trans. Roy. Soc., London, Series B, Vol. 204, pp. 179-200, 1913.

Pantanelli, E., *Ricerche Sulla Concentrazione del Liquide Circolante nei Terreni Libici;* Bul. Orto Bot. R., Univ. Napoli, T. 4, pp. 371-383.

[3] Hoagland, D. R., *The Freezing Point Method as an Index of Variations in the Soil Solution Due to Season and Crop Growth;* Jour. Agr. Res., Vol. XII, No. 6, pp. 369-395, 1918.

of the solution in these soils through the growing season by the freezing point method corroborates the conclusions drawn from the water extracts. The investigation also indicates that large amounts of nutrients are made available by cultivation, fallowing, and cropping and that, from the standpoint of the soil solution, the ordinary farm practices are inherently sound.

Hoagland's data regarding some of the soils studied is given in Table LXIII. The moisture content was approximately the same for each soil.

TABLE LXIII

THE CONCENTRATION OF THE SOIL SOLUTION IN PARTS PER MILLION FROM A GOOD AND POOR SOIL EACH FALLOWED OR CROPPED TO BARLEY.

DATE	FERTILE SOIL		POOR SOIL	
	FALLOW	CROPPED	FALLOW	CROPPED
July 10.....	2000	1200	1100	600
July 24.....	1700	500	800	200
Aug. 21.....	1800	700	1300	400
Oct. 23.....	4300	1900	2900	900
Dec. 18.....	3400	1500	1800	1000
Feb. 12.....	4200	1900	2700	1800
May 7.....	6700	3800	6300	3700

Further investigations of Hoagland with Martin [1] indicate that the effect of cropping on the soil solution persists for a considerable period. A marked relationship was also noted between the soil solution and the physical condition of the soil, due to a change in the colloidal matter with season. An increase in colloidal matter was noted when the soil solution was depleted of its solutes by plant activities.

[1] Hoagland, D. R., and Martin, J. C., *Effect of Season and Crop Growth on the Physical State of the Soil;* Jour. Agr. Res., Vol. XX, No. 5, pp. 397-404, 1920.

149. Other factors influencing the soil solution.—A number of other conditions, which are really phases of season, influence both the concentration and the composition of the soil solution. Among these are temperature, leaching, and the moisture content of the soil. As the soil warms up in the spring, reactions of all kinds are stimulated and an increase in concentration generally results. If considerable rain-water enters the soil, the soil solution is much diluted. It is also changed in composition, due to the equilibrium adjustments that of necessity occur. The following data from Bouyoucos [1] show the influence of change in moisture on the concentration of the soil solution:

TABLE LXIV

CONCENTRATION OF THE SOLUTION OF CERTAIN SOILS AT VARIOUS MOISTURE CONTENTS. LOWERING OF THE FREEZING POINT METHOD.

Soils	Moisture %	Concentration P. P. M.	Moisture %	Concentration P. P. M.
Sand	2.60	3,939	21.98	303
Sandy loam	8.30	13,639	21.53	606
Loam	11.18	13,780	20.97	848
Silt loam	17.40	20,153	34.76	1061
Clay	18.80	28,940	36.50	1030

If the soil is moistened beyond its water-holding capacity, it is obvious that drainage losses will occur, which will deplete the soil of valuable constituents. Increase of moisture, therefore, may modify the soil solution temporarily or permanently, according to conditions.

Tillage and the addition of various materials also have a

[1] Bouyoucos, G. J., *The Freezing Point Method as a New Means of Measuring the Concentration of the Soil Solution Directly in the Soil;* Mich. Agr. Exp. Sta., Tech. Bul. 24, 1915.

remarkable influence on the soil solution, especially increasing its concentration during the warmer seasons. Plowing and cultivation by stimulating biological activity may enhance nitrate production to a marked degree in a short time. Aëration will often increase the available mineral elements by the encouragement of reactions which favor solution. The addition of salts of various kinds has been shown by Bouyoucos [1] to influence the soil solution profoundly. The compounds added affected different soils in a diverse manner. When neutral salts were added, the soil solution was increased from 35 to 100 per cent. of the added strength of the salts. In the case of phosphate salts the increase was very much less.

150. The soil solution and productivity.—As the crop obtains its nutrients from the soil solution, there must be a direct relationship between the fertility of the soil and the concentration and composition of the soil solution. The data quoted from Hoagland indicate in a broad way that a fertile soil is capable of maintaining a more concentrated soil solution than is a poorer one. The work of other investigators amply corroborates this assumption.[2] One rather convincing experiment may be quoted.

Hall, Brenchley, and Underwood [3] analyzed the water extract from certain plats on the Rothamsted Experiment Station farm, the fertilizer treatment and the yields of which had been recorded for a long term of years. Complete analyses of the soil from the several plats were also made:

[1] Bouyoucos, G. J., *The Freezing Point Method as a Means of Studying Velocity Reactions Between Soils and Chemical Agents and Behavior of Equilibrium;* Mich. Agr. Exp. Sta., Tech. Bul. 37, 1917.

Also, *Rate and Extent of Solubility of Soils under Different Treatments and Conditions;* Mich. Agr. Exp. Sta., Tech. Bul. 44, 1919.

See also, Spurway, C. H., *The Effect of Fertilizer Salt Treatments on the Composition of Soil Extracts;* Mich. Agr. Exp. Sta., Tech. Bul. 45, 1919.

[2] See citations page 284.

[3] Hall, A. D., Brenchley, W. E., and Underwood, T. M., *The Soil Solution and the Mineral Constituents of the Soil;* Phil. Trans. Roy. Soc., London, Series B, Vol. 204, pp. 179-200, 1913.

TABLE LXV

YIELDS TO THE ACRE OF CROPS, AND COMPOSITION OF SOIL AND WATER EXTRACT OF SOIL. ROTHAMSTED EXPERIMENT STATION FARM. ENGLAND.

TREATMENT	YIELD TO THE ACRE (POUNDS)	COMPLETE ANALYSIS		WATER EXTRACT	
		P_2O_5 %	K_2O %	P_2O_5 P. P. M.	K_2O P. P. M.
Untreated.....	1276	.099	.183	.525	3.40
$N + K_2O$.....	2985	.102	.257	.808	30.33
$N + P_2O_5$.....	3972	.173	.248	3.900	3.88
$N + K_2O + P_2O_5$..	5087	.182	.326	4.025	24.03
Farm manure....	6184	.176	.167	4.463	26.45

151. Summary.—The solution as it exists in a normal soil is highly dynamic. Its concentration and composition are fundamentally governed by rate of solution, by absorption, and by the amounts of the various solutes in the solution itself. Many factors are active in preventing a condition of equilibrium between these three phases. Those of especial importance are season and crop. Temperature, moisture content, and leaching are subfactors of season. Tillage of all kinds and the addition of manures, lime, and fertilizers are practical means of modifying the soil solution more to adequately meet the needs of the crop. In fact, all of the common practices so successfully used in economic soil management attain their end through a modification and control of the soil solution.

CHAPTER XV

THE REMOVAL OF NUTRIENTS FROM THE SOIL BY CROPPING AND LEACHING

The soil solution, because of its dynamic character, offers two sources of loss for nutrient materials, one of which should be economically encouraged, while the other should be reduced by suitable control to as low a point as is consistent with good soil management. These two sources of exhaustion are (1) cropping and (2) leaching or drainage. One is a legitimate expenditure; the other is a waste, which within certain limits in a humid region is unavoidable.[1]

152. Intake of water by plants—osmosis.—Plants obtain their raw materials from the air and the soil, the former furnishing the carbon and the oxygen, most of the water and the nutrients proper coming from the soil. Although many constituents, some necessary and some incidental, pass into the plant from the soil, for convenience of discussion two groups may be established: (1) water, and (2) nutrients proper. It must be kept in mind, however, that water, while performing certain mechanical functions, has a nutrient relationship also.

The most important mechanical principle governing the absorption of water by the plant is *osmosis*.[2] The abstract phenomenon should be clearly in mind before its plant relationships are considered. A bag of collodion (pig's bladder or parchment paper will do as well) is filled with a strong solu-

[1] Gases, such as carbon dioxide, nitrogen and possibly ammonia, may be lost from the soil also.

[2] Water may also be taken up by colloidal absorption which is called imbibition. This is common in seeds.

tion of cane-sugar. The walls of such a bag are semi-permeable, that is, certain materials will pass through readily while others will pass but slowly. For example, the sugar molecules penetrate with difficulty, while the water finds the walls of the bag but a slight obstacle.

If this collodion bag with its sugar solution is attached to a capillary tube and immersed in pure water, it at once becomes distended and the liquid will rise in the capillary tube, indicating an unequal pressure within the system. The pressure develops because of the separation of the pure water and the sugar solution by a membrane that is penetrated at different rates by the molecules and ions in contact with it. A tendency towards equalization of course occurs and, as the water moves in faster than the sugar moves out, a pressure is developed within the bag which becomes apparent by the rise of the liquid in the capillary tube. Such a phenomenon is called osmosis and the pressure osmotic pressure. Such force probably has much to do with the movement of plant saps and fluids. Under such conditions as those maintained in the experiment, the water tends to move from the dilute solution to the more concentrated one.

Suppose the collodion bag be considered as typical of the cells, which form the feeding surface of an active rootlet, and the sugar solution the relatively concentrated and partially colloidal cell contents. The water outside the bag will, of course, represent the dilute soil solution which bathes the roots. With such substitutions it can readily be seen why the plant exerts an osmotic "pull" and how the water moves through the cell-wall. Such a transfer will continue until the movement of the water in the soil becomes too slow for normal plant activities. Wilting then occurs. (See Fig. 51.)

In alkali soils, where the soil solution becomes very concentrated, the process above described may be reversed. Outward osmosis then occurs and plasmolysis[1] may result.

[1] Plasmolysis is a separation of the plasma from the cell-wall due to a

Bouyoucos [1] has suggested that the phenomena of wilting may be due, at least partially, to plasmolysis since he has shown by observing the depression of the freezing point that the soil solution becomes very concentrated at low moisture contents.

Such a conception of water absorption is simple, yet it often leads to erroneous ideas regarding the intake of nutrients by plants. The amount of any particular nutrient absorbed by the plant is not determined by the quantity of water taken up, since water and nutrients enter more or less independently. The large amount of water imbibed by the plant, later to be lost by transpiration, cannot be accounted for on the basis of a very dilute soil solution and the necessity of rapid transpiration in order to facilitate the entrance of sufficient nutrient substance.

153. Absorption of nutrients by plants—diffusion.—The solution in a normal fertile soil is not only rather dilute *in toto* but a great proportion of the nutrients therein are in the ionic condition. While both molecules and ions are presented to the absorbing surfaces of the plant, it is only the latter that penetrate to any great extent, although some materials, especially those of an organic nature, do enter in a molecular condition. The presence of water is, of course, necessary for both ionic and molecular penetration, but only as a medium for *diffusion.* Its movement into the plant is, therefore, of no very great moment in the actual diffusion process, as the phenomenon is called, although the approach of the nutrients to the feeding surfaces is considerably influenced by capillary activity.

The tendency of diffusion is to equalize the concentration of a solution as to the ions and molecules of its solute, the molecules and ions of different salts moving more or less inde-

loss of water. It is a shrinkage of the protoplasm and when carried beyond a certain point permanently injures the cell.

[1] Bouyoucos, G. J., *The Freezing Point Method as a New Means of Measuring the Concentration of the Soil Solution Directly in the Soil;* Mich. Agr. Exp. Sta., Tech. Bul. 24, 1915.

pendently. The absorption of nutrients by plants, in its simplest analysis, is but a working out of this phenomenon. Thus, if the concentrations of K^+ ions is high in the soil solution and low within the cell, the potassium will move inward in response to diffusion forces, providing, of course, the ions can pass through the cell wall. This penetration is entirely independent of the entrance of water, as far as the

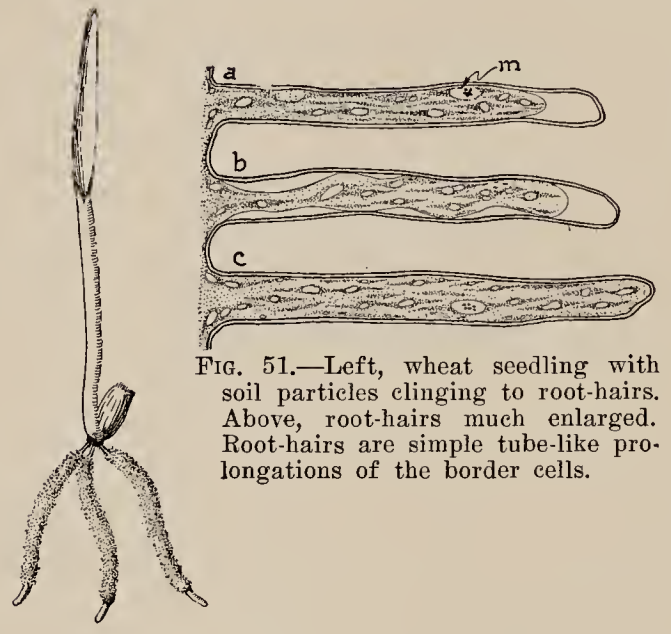


FIG. 51.—Left, wheat seedling with soil particles clinging to root-hairs. Above, root-hairs much enlarged. Root-hairs are simple tube-like prolongations of the border cells.

movement of the latter is concerned. Moreover, the equalization of one ion is more or less unrelated to the concentration equilibrium of any other. The osmosis of the water, on the other hand, is a phenomenon dependent on sum-total concentration plus the semi-permeable membrane.

154. Differential diffusion.—The intake of nutrients is by no means as simple as the above explanation might lead one to assume, due to the complications interposed by the presence of a semi-permeable membrane. The passage of ions and molecules through the cell-wall and the protoplasmic membrane

may be a simple mechanical infiltration, although it is probably accompanied by a chemical reaction, or by a change in the colloidal state of the membrane or both. Moreover, different ions and molecules do not pass through the same cell-wall [1] with equal facility. Thus, one kind of ions may pass through very readily while another kind may encounter extreme difficulty in responding to diffusion tendencies.

Differential diffusion may be ascribed to two conditions: (1) different relationships between the cell-wall and the ions and molecules of the entering material; and (2) differences in the rate at which the entering molecules and ions are utilized in the metabolic activities of the cell in particular and the plant as a whole. The first case has been partially explained. If a compound ionizes into A and B ions and if A ions, due to their relationship to the colloidal cell-wall, enter more easily, a residue of B ions will be left in the soil solution.

The second case may be illustrated by assuming the presence of potassium chloride in the soil solution. It ionizes K^+ and Cl^- ions. Now conceive that these ions diffuse through the cell-wall with equal facility in response to equilibrium tendencies. If the potassium ions are used by the cell as rapidly as they enter and are removed from solution, more potassium will be absorbed. This might continue until the potassium ions in the soil solution become much reduced in number. If the chlorine, on the other hand, is but slightly utilized by the plant, little will be drawn from the soil after the initial equalization. Thus, a residue of chlorine might be left from this type of differential absorption. This application of diffusion principles shows the possibility, or even more, the probability of plants leaving residues in the soil solution. What the residues from different fertilizers may be and what is the practical importance of such differential actions are pertinent questions.

[1] The term cell-wall as used here refers to the cell-wall proper plus the protoplasmic membrane.

155. Fertilizer residues may be developed in two general ways: (1) by selective absorption by the soil; and (2) by differential diffusion into the plant. Regarding the first case (see par. 141), it has already been established that soils ordinarily absorb the basic ions more strongly than the acid radicals, thus tending to leave an acid residue in the soil solution. Sodium nitrate, ammonium sulfate, calcium nitrate, potassium chloride and potassium sulfate, therefore, tend to produce an acid residue, when they are first added to a soil.

The final result, however, cannot be determined until the action of the crop is known. If the crop especially utilizes the cation or basic radical, it will intensify the selective absorption of the soil and a still more pronounced acid residue will result. This would be the case with ammonium sulfate, potassium sulfate, and potassium chloride. If, however, the anion or acid radical is utilized to the greater extent, the action of the soil absorption would be nullified and an alkaline residue would tend to develop. This is especially true with sodium nitrate when applied in large amounts over a term of years, the physical condition of the soil becoming impaired due to the presence of sodium carbonate.[1]

One other condition is possible. If the plants should use the cation and anion of a fertilizer salt in equal proportions, no residue would result. This seems to happen to an approximate degree with ammonium nitrate, potassium phosphate, potassium nitrate, and ammonium phosphate. Such salts are extremely valuable in long-continued experiments, where the disturbing effects of fertilizer residues are to be avoided. Monocalcium phosphate, the important constituent of acid phosphate, needs especial consideration. When added to the soil, it immediately reverts to the tricalcium form if active calcium is present.[2] Even with the large amount of gypsum

[1] Hall, A. D., *The Effect of the Long Continued Use of Sodium Nitrate on the Constitution of the Soil;* Trans. Chem. Soc. (London), Vol. 85, pp. 950-971, 1904.

[2] $CaH_4(PO_4)_2 + 2CaH_2(CO_3)_2 = Ca_3(PO_4)_2 + 4H_2O + 4CO_2$

carried by acid phosphate, the effect does not seem to be towards acidity even after long periods of application.[1]

This discussion, brief as it is, brings out a little studied phase of crop and fertilizer interaction. How the plant utilizes a particular fertilizer after it is once in the soil, what residues are left, and the importance of such residues, are questions of fundamental concern. The possibility of plants influencing the soil and the fertilizers added, as well as the soil and fertilizer influencing the crop, is well worth attention.

156. Do plants directly aid in the preparation of their nutrients?—The conception commonly held regarding the plant is that its direct relation to the soil is more or less passive. Indirectly, of course, it may exert a considerable influence on the availability of the nutrients. In view of the knowledge regarding fertilizer residues and the new concepts as to possible root exudates, the idea that the plant may directly aid in the preparation of its own nutrients is becoming more and more plausible.

Such influences, if recognized, might occur in three ways: (1) through the action of carbon dioxide, known to be given off in large amounts by roots; (2) through the influence of organic and inorganic acids other than carbonic acid; and (3) by catalytic agents, enzymic or non-enzymic.

In a rich, moist soil the number of root-hairs is very large and the relationship between the rootlets and the soil particles very intimate. When in contact with a particle of soil or colloidal complex, the root-hair in many cases almost incloses it, and by means of its mucilaginous wall forms a contact so close as to make the solution held between the particle and the cell-wall distinct from that in the soil proper. Carbon dioxide, excreted under such conditions, may assume a solvent power entirely unique and independent of the amount produced.

[1] Conner, S. D., *Acid Soils and the Effect of Acid Phosphate and Other Fertilizers Upon Them;* Jour. Ind. and Eng. Chem., Vol. 8, No. 1, pp. 35-40, Jan. 1916.

The plant might thus facilitate special conditions and aid materially in the preparation of its own nutrients.

Sachs,[1] and later other investigators, grew plants of various kinds in soil and other media in which was placed a slab of polished marble or dolomite or calcium phosphate, covered with a layer of washed sand. After the plants had made sufficient growth the slabs were removed, and on the surfaces were found corroded tracings, corresponding to the lines of contact between the rootlets and the minerals.

Czapek[2] repeated the experiments of Sachs, using plates of gypsum mixed with the ground mineral that he wished to test, and this mixture he spread over a glass plate. Czapek found that, while plates of calcium carbonate and of calcium phosphate were corroded by the roots, plates of aluminum phosphate were not. He concludes that if the tracings are due to acids excreted by the roots, these acids must be those that have no solvent action on aluminum phosphate. This would limit the excreted acids to carbonic, acetic, proprionic, and butyric. By means of micro-chemical analyses of the exudations of root-hairs grown in a water-saturated atmosphere, Czapek found potassium, magnesium, calcium, phosphorus, and chlorine in the exudate. He concludes that the solvent action of roots is due to acid salts of mineral acids, particularly acid potassium phosphate. He has not proved, however, that the exudations were not from dead root-hairs or from the dead cells of the root cap. In either case they would have some solvent action, but whether sufficient to make them of importance is doubtful. This objection makes the possible exudation of organic and inorganic acids somewhat questionable.

Molisch[3] found that root-hairs secrete a substance having

[1] Sachs, J., *Auflösung des Marmors dureh Mais-Wurzlen;* Bot. Zeitung, 18 Jahrgang, Seite 117-119, 1860.

[2] Czapek, J., *Zur Lehre von den Wurzelausseheidung;* Jahrb. f. Wiss. Bot., Band 29, Seite 321-390, 1896.

[3] Molisch, H., *Über Wurzelausscheidungen und deren Einwirkung auf*

properties corresponding to those of an oxidizing enzyme. His work has been repeated by others, who have failed to obtain similar results, but lately Schreiner and Reed [1] have demonstrated an oxidizing action of roots that is apparently due to a peroxidase. Oxidation alone, however, would hardly suffice to account for the solvent action accompanying the development of roots, although it is doubtless an important function and useful in other ways.

Schreiner and Sullivan [2] have demonstrated the presence of reducing substances in media in which plants were growing. This work has recently been corroborated by Lyon and Wilson,[3] working with maize, oats, peas, and vetch. They found that the solutions in which the plants had been growing exhibited both reducing and oxidizing phenomena. Reducing substances were always present, but whether oxidizing materials were so consistently produced could not be definitely decided. The peroxidases were rendered inactive by boiling the solutions. The reducing substances did not always disappear with such treatment. This would throw some doubt upon the enzymic character of the reducing materials and suggest that non-enzymic catalytic exudates are a possibility.

The interstices between the larger particles of a normal soil are at least partially filled with colloidal material of a more or less gel-like nature. Moreover, the surfaces of some soil grains may be somewhat coated with the same material. Roots of growing plants have been found to cause coagulation of at least some colloids, possibly by leaving an acid residue in the nutrient solution by reason of the selective

Organische Substanzen; Sitzungsber. Akad. Wiss. Wien-Math. Nat., Band 96, Seite 84-109, 1888. Abstract in Chem. Centrlb. f. Agr. Chem., Band 17, Seite 428, 1888.

[1] Schreiner, Oswald, and Reed, H. S., *Studies on the Oxidizing Powers of Roots;* Bot. Gazette, Vol. 47, p. 355, 1909.

[2] Schreiner, O., and Sullivan, M. K., *Studies in Soil Oxidation;* U. S. Dept. Agr., Bur. Soils, Bul. 73, 1910.

[3] Lyon, T. L., and Wilson, J. K., *Liberation of Organic Matter by Roots of Growing Plants;* Cornell Agr. Exp. Sta., Memoir 40, July, 1921.

absorption of bases and rejection of the acid radicals of the dissolved salts. It is conceivable that the root-hairs, by removing bases from the solution existing between the cell-wall and the colloidal covering of the soil particle, may cause coagulation of the colloidal matter and thus liberate the nutrient materials held by absorption. The liberated material, being of a readily soluble nature, would be taken up by the solution between the rootlet and the soil particle, from which the root-hair could readily absorb it. Such an hypothesis would account for the ability of plants to obtain a quantity of nutrients far in excess of that accounted for by the solvent action of pure water, and even beyond what many investigators are willing to attribute to the solvent action of water charged with carbon dioxide.

157. The present status of the question.—The available evidence on excretion of acids other than carbonic by the roots of plants does not admit of any very satisfactory conclusion as to their relative importance in the acquisition of plant nutrients. There can be no doubt, however, that carbon dioxide resulting from root exudation and from decomposition of organic matter in the soil plays a very prominent part in this operation. The very large quantity of carbon dioxide in the soil, amounting in some cases to nearly 10 per cent. of the soil air, or several hundred times that of the atmospheric air, must aid greatly in dissolving the soil particles.

Whatever may be the concentration of the soil-water, it seems probable that the liquid that is found where the root-hair comes in contact with the soil particle, and that is separated, in part at least, from the remainder of the soil-water, must have a composition different from that found elsewhere in the soil. Many plants grown in solutions of nutritive salts have few or no root-hairs, but absorb through the epidermal tissue of the roots. The special modification by which the root-hairs come in intimate contact with the soil particle and almost surround it, indicates a direct relation between the

soil particles and the plant, as well as between the soil-water and the plant. Such a condition complicates in no small degree the practical questions of soil management and plant nutrition.

158. Why crops vary in their ability to thrive on different soils.—It is very commonly recognized that crops of different kinds vary in their ability to obtain nourishment from the soil. The difference between the nitrogen, phosphoric acid, potash, and lime taken up by an average corn crop and a wheat crop of average size is striking. The terms "weak feeders" and "strong feeders," so often heard, indicate the practical field relationships. Aside from the fact that crops do not all need the same quantities of nutrients these differences in ability to grow normally on different soils may be due either to (1) a larger absorbing system or (2) a more active absorptive capacity.

Plants with large root systems may be expected to absorb greater amounts, not only of water but of nutrients also.[1] Such a development is especially important in time of drought and in addition gives the plant a greater area from which to draw nutrients. Water, as well as nutrients, does not move through any great distance towards the imbibing and absorbing surfaces. Root development, while of some importance in explaining the differences in the feeding capacities of plants, is probably by no means as important as differences in the absorption activity.

The absorptive activity of a plant under any given condition of soil, climate, and stage of growth depends on: (1) the concentration and composition of the cell-sap; (2) the character of the cell-wall; (3) the activity of the cell in elaborating and removing from solution the materials absorbed; (4) the extent to which exudates—whether these be carbon

[1] Gile, P. L., and Carrero, P. L., *Absorption of Nutrients as Affected by the Number of Roots Supplied with the Nutrient;* Jour. Agr. Res., Vol. IX, No. 3, pp. 73-95, 1917.

dioxide, organic or mineral acids and their salts or enzymes —act on the colloidal and non-colloidal soil constituents; and (5) synergistic relationships in the soil solution or the cell-wall.

The concentration and composition of the cell-sap determines not only the osmotic relationship but has much to do with diffusion tendencies. The ability of the plant to obtain water and nutrients is thus directly affected by such conditions. The character of the cell-wall has of course an important influence on such phenomena. If the cell-wall is easily penetrated, it may greatly facilitate the absorbing capacity of the plant. If it is slowly penetrated or exerts special differential influences, it might have a great deal to do with the differences observed between certain plants. The character of the cell-wall has already been shown to be involved in the development of certain residues in the soil.

The rate at which materials are utilized within the plant is also a factor. If ions or molecules are used rapidly and thus removed from solution, the diffusion of similar ions and molecules is hastened. Such activity would also influence osmotic relationships to a marked extent. This has already been discussed under differential diffusion.

It is readily conceivable that exudates, insofar as they are capable of directly affecting the solubility of nutrients, might produce marked differences between plants as far as their absorbing activities are concerned. A crop producing active exudates of any kind should be able, other conditions being equal, to grow to better advantage, especially on a soil in which the necessary nutrients are somewhat unavailable.

The absorption of electrolytes by plants seems to be influenced by the presence of other nutrient ions. True [1] has shown that K^+ ions when accompanied by Ca^{++} ions are readily absorbed by the seedlings of certain plants. When the same

[1] True, R. H., *The Function of Calcium in the Nutrition of Seedlings;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 91-107, 1921.

concentration of potassium is offered in single solution, this nutrient is more or less neglected by the seedlings. This relationship, by which the calcium ions make the potassium physiologically available, is spoken of by True as *synergism* [1] and probably has a great deal to do with the penetration of nutrient ions into the plant. It is no doubt of considerable importance in acid soils where the active calcium is low.

159. The absorptive capacity of different crops.— Cereals have the power of utilizing the potassium and phosphorus of the soil to a considerable degree, but they generally require fertilization with nitrogen salts. Most of the cereals, such as wheat, rye, oats, and barley, take up the principal part of their nitrogen early in the season, before the nitrification processes are sufficiently operative to furnish a large supply of nitrogen; hence nitrogen is the fertilizer constituent that usually gives good results, and should be added in a soluble form. Wheat, in particular, needs a large amount of available nitrogen early in its spring growth. Since it is a "delicate feeder," it does best after a cultivated crop or a fallow, by which the nitrogen has been converted into a soluble form. Oats can make better use of the soil nutrients and do not require so much manuring. Maize is a very "coarse feeder," and, while it removes a large quantity of plant nutrients from the soil, it does not require that this shall be added in a soluble form. Farm and other slowly acting manures may well be applied for the maize crop. The long growing period required by maize gives it opportunity to utilize the nitrogen as it becomes available during the summer, when ammonification and nitrification are active. Phosphorus is the substance usually most needed by maize.

Grasses, when in meadow or in pasture, are greatly benefited by manures. They are less vigorous "feeders" than the cereals, have shorter roots, and, when allowed to grow for more than one year, the lack of aëration in the soil causes the

[1] The term is used here in the sense of coöperation.

decomposition of soil organic matter to decrease. There is usually a more active fixation of nitrogen in grass lands than in cultivated lands, but this nitrogen becomes available very slowly.

Different soils and climatic conditions necessitate varied methods of manuring for grass. Farm manures may well be applied to meadows in all situations, while the use of available nitrogen in commercial fertilizers is generally profitable.

Most of the leguminous crops are deep-rooted and are vigorous "feeders." Their ability to take nitrogen from the air makes the use of that fertilizer constituent unnecessary except in a few instances, such as young alfalfa on poor soil, where a small application of nitrate of soda is usually beneficial. Phosphoric acid and often lime are the substances most beneficial to legumes on most soils.

Many crops will utilize very large quantities of nutrients if they are in a form in which they can be used. Phosphates and nitrogen are the substances generally required, the latter especially by beets and carrots. In growing vegetables the object is to produce a rapid growth of leaves and stalks rather than seeds, and often this growth is made very early in the season. As a consequence a soluble form of nitrogen is very desirable. Farm manure should also have a prominent part in the treatment, as it keeps the soil in a mechanical condition favorable to the retention of moisture, which vegetables require in large amounts, and it also supplies needed fertility. The very intensive method of culture employed in the production of vegetables necessitates the use of much greater quantities of manures than are used for field crops, and the great value of the product justifies the practice.

160. Quantities of nutrients removed by crops.—The utilization of nutrient substances by crops is a constant source of loss of fertility to agricultural soils. In a state of nature the loss in this way is comparatively small, as the native vegetation falls on the ground, and in the process of decomposi-

tion the ash is almost entirely returned, while there is a large gain of organic matter and often an increase in nitrogen as well. Under natural conditions the soil usually increases in fertility; for, while there is some loss through drainage and other sources, this is more than counterbalanced by the action of the natural agencies of disintegration and decomposition, while the fixation of atmospheric nitrogen affords a constant, though small, supply of that important soil ingredient.

When land is placed under cultivation a very different condition is presented. Crops are removed and only partially returned at best to the soil as manure and crop residue. A certain proportion of the soil nutrients are, therefore, permanently withdrawn. The point of vital importance, however, is that only a part of the total supply of soil constituents will ever become available, the portion withdrawn each year by cropping being a more serious consideration than is generally supposed.

The following table, computed by Warington,[1] shows the quantities of nitrogen, potash, phosphoric acid, lime and sulfur trioxide [2] removed from an acre of soil by some of the common crops. The entire harvested crop is included.

TABLE LXVI

CROP	YIELD	ASH (LBS.)	N (LBS.)	K_2O (LBS.)	CaO (LBS.)	P_2O_5 (LBS.)	SO_3 (LBS.)
Wheat.....	30 bushels	172	48	28.8	9.2	21.1	15.7
Barley.....	40 bushels	157	48	35.7	9.2	20.7	14.3
Oats.....	45 bushels	191	55	46.1	11.6	19.4	19.7
Maize.....	30 bushels	121	43	36.3	...	18.0	12.0
Meadow Hay	1½ tons	203	49	50.9	32.1	12.3	11.3
Red Clover..	2 tons	258	102	83.4	90.1	24.9	15.4
Potatoes....	6 tons	127	47	76.5	3.4	21.5	11.5

[1] Warington, R., *Chemistry of the Farm;* pp. 64-65, London, 1894.

[2] From Hart, E. B., and Peterson, W. H., *Sulphur Requirements of Farm Crops in Relation to the Soil and Air Supply;* Wis. Agr. Exp. Sta., Res. Bul. 14, 1911.

Before the question of possible soil exhaustion can be discussed adequately, the losses of nutrients in the drainage water must be considered as another source of loss in addition to the cropping influences already noticed.

161. Qualitative composition of drainage water.—In theory, at least, the qualitative composition of drainage water should be the same as that of the soil solution; that is, in it should be found all of the common bases and acid radicals. Actually, however, due to the absorptive power of the soil, certain constituents appear in very slight amounts. Phosphorus, for example, often occurs in drainage only in traces, as do the nitrites, ammonia, and carbonates. The principal bases lost by leaching are calcium, magnesium, potassium, and sodium. The important acid radicals of drainage water are the nitrates, chlorides, sulfates, and bicarbonates.

As might be expected, the constituents appearing in drainage are extremely variable not only when different soils are compared but also within the same soil at different periods. Phosphorus may be leached from some soils in measureable quantities, while from others the amount may be negligible. Nitrate nitrogen is usually an important constituent in all drainage water during the summer, especially that from a bare soil. In the winter and early spring nitrates decrease in amount. The method of soil treatment as to cultivation, manuring, liming, or fertilizing may also markedly influence the qualitative composition of the water draining from field soil.

162. Quantitative composition of drainage water.—While but little reliable data regarding the composition and especially the concentration of the soil solution are available at the present time, much exact information has been obtained regarding drainage water. The concentration of drainage water is much lower than that of the soil solution and much less variable. The total concentration seems to be governed more by the amount of water leaching through than by any other factor. Other seasonal conditions of course come into

play. In total concentration, drainage water seldom exceeds 500 parts per million. It is thus much more dilute than the average soil solution. This difference holds for the separate constituents as well as for the concentration *in toto*.

The following data, as compiled by Hall,[1] give some idea of the quantitative composition of the drainage water from the clay loam soil of the Rothamsted Experimental Farm. The drainage water was obtained from tile drains, a line of which extended under each of the variously treated plats. The data is a mean of five collections, 1866 to 1868.

TABLE LXVII

Treatment	Parts per Million Based on Solution										
	N_2O_5	NH_3	P_2O_5	K_2O	CaO	MgO	Na_2O	Fe_2O_3	Cl	SO_3	SiO_2
No manure.....	3.9	.12	.63	1.7	98.1	5.1	6.0	5.7	10.7	24.7	10.9
Farm manure, 14 tons	16.1	.16	—	5.4	147.4	4.9	13.7	2.6	20.7	106.1	35.7
Minerals[2] only..	5.1	.13	.91	5.4	124.3	6.4	11.7	4.4	11.1	66.3	15.4
Minerals plus 600 lbs. $(NH_4)_2SO_4$	16.9	.27	.17	2.7	197.3	8.9	10.6	2.7	39.4	89.7	20.9
Minerals plus 550 lbs. $NaNO_3$...	18.4	.24	—	4.1	118.1	5.9	56.1	5.1	12.0	41.0	10.6

It is immediately noticeable that ammoniacal nitrogen and phosphoric acid are lost in drainage to but a slight degree. Calcium appears in the highest concentration with sulfur next. Nitrates and potash are present in appreciable quantities but are quite variable.

The influence of treatment is particularly obvious on the parts per million of nitrate nitrogen, lime, and sulfur appearing in the drainage, the addition of farm manure increasing all of these constituents as well as the concentration of the potash, soda, and chlorine. The application of sodium nitrate increased the nitrate nitrogen as well as the soda, potash, and

[1] Hall, A. D., *The Book of the Rothamsted Experiments;* pp. 237-239, New York, 1917.

[2] By minerals are meant the phosphoric acid, potash, lime, and other constituents left as ash when plants are burned.

lime. The two latter constituents are probably liberated by basic exchange. The addition of any fertilizer seems especially to increase the lime in the drainage water. This is probably due to the development of acid fertilizer residues. In general, it seems that the more productive the soil and the heavier the fertilization, the higher the concentration of the constituents in the drainage water.

It is not always the case, however, that a manured soil loses more nutrient material than an unfertilized one. Gerlach[1] reports experiments with soil tanks at the Bromberg Institute of Agriculture, in which five soils rationally fertilized yielded larger crops and lost in the main less nitrogen and lime in the drainage water than the same soils unmanured. The loss of potash was slightly greater from the manured than from the unmanured soils. Apparently the stimulation that the plants received from the fertilizer enabled them to make such a good growth that they absorbed more soluble nitrogen and lime in excess of the unfertilized plants than was added in the fertilizer, and nearly as much potash.

The most serious losses of plant nutrients in drainage are those of the nitrogen and calcium, both of which losses are to a certain extent unavoidable. These losses are also very closely related, rising and falling together. Nitrogen is lost as the nitrate while the calcium is leached out due to the presence of the bicarbonate and nitrate radicals. While loss of lime goes on continually, it is of necessity particularly large during periods of rapid nitrate accumulation. Nitrogen is a high-priced fertilizer constituent, while a continued loss of lime tends to produce soil acidity. About the only means of conserving either of these constituents is to maintain a crop on the soil, especially during the warmer seasons.

[1] Gerlach, M., *Über die durch Sickerwasser dem Boden Entzogenen Menge Wasser und Nahrstoffe;* Illus. Landw. Zeitung, 30 Jahrgang, Heft 95, Seite 871-881, 1910. Also, *Untersuchungen über die Menge und Zusammensetzung der Sickerwasser;* Mitt. K. W. Inst. f. Landw. in Bromberg, Band 3, Seite 351-381, 1910.

163. Quantities of nutrients removed by drainage and cropping.—Now that an adequate conception has been presented regarding the composition of soil drainage water and also of the nutrients removed by cropping, it is interesting to note what the combined result may be on the same soil. Such information can be obtained only in a few instances. The following data from the lysimeters at the Cornell Experiment Station [1] are valuable in this respect.[2] The soil used was a Dunkirk silty clay loam.

TABLE LXVIII

AVERAGE ANNUAL LOSS OF NUTRIENTS BY PERCOLATION AND CROPPING. CORNELL LYSIMETER TANKS. AVERAGE OF 10 YEARS.

CONDITION	POUNDS TO THE ACRE PER YEAR				
	N	P_2O_5	K_2O	CaO	SO_3
Drainage losses					
Bare.....	69.0	—	86.4	557.0	132.0
Rotation....	7.3	—	68.7	345.9	108.5
Grass.....	2.5	—	74.0	363.8	111.0
Crop removal					
Bare.....	—	—	—	—	—
Rotation....	70.5	43.5	105.4	24.3	41.0
Grass.....	54.4	28.6	74.0	12.8	29.2
Total loss					
Bare.....	69.0	—	86.4	557.0	132.0
Rotation....	77.8	43.5	174.1	370.2	149.5
Grass.....	56.9	28.6	158.0	376.6	140.2

[1] Unpublished data, Cornell Agr. Exp. Sta., Ithaca, N. Y.

[2] A study was made at the New Jersey Experiment Station of the nitrogen losses from a loam soil in cylinders under a five-year rotation of corn, oats, wheat and timothy for 20 years, treated in various ways as to lime, manure and fertilizers. The average loss of nitrogen from the surface ten inches of soil for 15 years was 103 pounds annually due to cropping and leaching. Data were obtained by analyzing the soil and the crops. Lipman, J. G., and Blair, A. W., *Nitrogen Under Intensive Cropping;* Soil Sci., Vol. XII, No. 1, pp. 1-16, July, 1921.

The first outstanding feature of the above table is the control on drainage losses exerted by cropping. The loss of nitrate nitrogen is reduced to an exceptionally low figure, while the saving of potash, sulfur, and lime is quite appreciable. No phosphoric acid is lost even from the bare soil. The losses due to cropping and leaching combined from a planted soil are generally but little greater than the drainage losses alone from a soil kept continuously bare except in the cases of the phosphoric acid and the potash.

The next point of interest is the difference in the nutrients removed by a rotation of crops, such as maize, oats, wheat, and hay as compared with permanent meadow. The latter, although absorbing less nutrients than the rotation crops, exert as marked a conserving effect on the nutrients appearing in the drainage as do the crops in rotation. The comparative removal of nutrients from the soil by cropping and leaching are well shown by the following diagram, in which the weight of the symbols indicates where the loss of any particular nutrient is the greater.

RELATIVE LOSSES OF NUTRIENTS FROM A PLANTED SOIL THROUGH CROPPING AND DRAINAGE

	Nitrogen	Phosphoric acid	Potash	Lime	Sulfur Trioxide
Cropping loss.....	**N**	**P_2O_5**	**K_2O**	CaO	SO_3
Drainage loss....	N	P_2O_5	**K_2O**	**CaO**	**SO_3**

164. Possible exhaustion of the soil.—It is interesting at this point to compare the amounts of nutrients removed annually from a soil cropped in rotation with the amounts which are present in an average soil to the depth of four feet. Assuming reasonable figures for the pounds of sulfur trioxide, lime, phosphoric acid, nitrogen, and potash and considering that these nutrients are wholly available, the following sig-

nificant data are obtained. The losses of nutrients by drainage and rotation cropping are from the figures already quoted regarding the Cornell lysimeter soils.

TABLE LXIX

SHOWING THE NUMBER OF YEARS A SOIL TO THE DEPTH OF FOUR FEET WOULD SUPPLY NUTRIENTS FOR CROP GROWTH, PROVIDING THAT ALL OF THESE CONSTITUENTS WERE UNIFORMLY AVAILABLE

CONSTITUENTS	POUNDS TO THE DEPTH OF FOUR FEET	POUNDS REMOVED ANNUALLY BY CROPPING AND DRAINAGE	YEARS
SO_3	12,000	84.5 [1]	142
CaO	85,000	370.2	229
P_2O_5	16,000	43.5	367
N	15,000	46.8 [1]	303
K_2O	250,000	174.1	1,435

While the subsoil supplies large amounts of plant nutrients, it must be remembered that only a small proportion of the soil constituents, especially the phosphoric acid and potash, ever become available either in surface or subsoil. Moreover, crop yields decrease as the nutrients, even those most readily available, are reduced. The above figures for duration of crop growth are, as a consequence, merely conventional but they indicate the probability of even a very fertile soil becoming quickly exhausted.

Moreover, when it is considered that the soil must be depended on to furnish food for humanity and domestic animals as long as they shall continue to inhabit the earth, the supply of plant nutrients becomes a matter of grave concern.

The visible sources of supply, to replace or supplement

[1] Sixty-five pounds of SO_3 are added an acre each year in rainwater while 31 pounds of N are added yearly to the acre in rain and through the free-fixing activity of organisms (pars. 222, 236 and 238).

those in the soils now cultivated, are, for the mineral substances, the subsoil and the natural deposits of phosphates, potash salts, and limestone; and for nitrogen, deposits of nitrate, the by-products of coal distillation, and the nitrogen of the atmosphere. The last of these is inexhaustible, and the exhaustion of the nitrogen supply, which a few years ago was thought to be a matter of less than half a century, has now ceased to cause any apprehension.

The conservation or extension of the supply of mineral nutrients is now of extreme importance. The utilization of city refuse and the discovery of new mineral deposits are developments well within the range of possibility, but neither of these promises to afford more than partial relief. The utilization of the subsoil through the gradual removal by natural agencies of the topsoil will, without doubt, tend constantly to renew the supply. The removal of topsoil by wind and water erosion is, even on level land, a very considerable factor. The large amount of sediment carried in streams immediately after a rain, especially in summer, gives some idea of the extent of this shifting. This affects chiefly the surface soil, and thereby brings the subsoil into the range of root action.

There is little doubt that a moderate supply of plant nutrients will always be available in most soils, but for progressive agriculture the use of green-manures, legumes and farm manures must be supplemented by judicious and economical application of lime and certain fertilizer constituents.

CHAPTER XVI

CHEMICAL ANALYSIS OF SOILS

No PHASE of soil science has received as much popular recognition as chemical analysis, nor is any other technical soil procedure so little understood in general and at the same time so greatly overrated. Many persons feel that a soil analysis should completely solve the many problems, both theoretical and practical, regarding the economic management of the soil, especially as to its fertilizer needs. In the light of such general misunderstanding in regard to the research and applied value of chemistry to soils, a consideration of the question seems opportune at this point, especially as the discussion of the phenomena of absorption and the characteristics of the soil solution have just been presented.

For convenience in treatment, chemical analyses, as applied to soils, may be grouped under two heads—total or bulk analyses and partial or extraction methods. In the former the total amount of certain constituents are determined regardless of their chemical combinations and character. In the latter group of methods only a portion of certain important materials are removed and analyzed, the chemical combination being to a certain extent a factor in the amount of any constituent extracted.

165. Bulk analysis—organic carbon and nitrogen.[1]—

[1] The sampling of the soil is an important consideration in any analytical work. The sample should be representative and is best taken with a soil auger. In sampling small areas, such as plats, a number of borings are usually made to the depths required and thoroughly mixed. This composite is quartered until a sample of the required size

The methods of determining the amount of organic matter in any soil have already been discussed (par. 60), the conclusion being that the figure for organic carbon, or this figure multiplied by 1.724, was the most reliable indication of the organic content of a soil. The bomb method is cited as one of the more suitable procedures for obtaining the organic soil carbon.

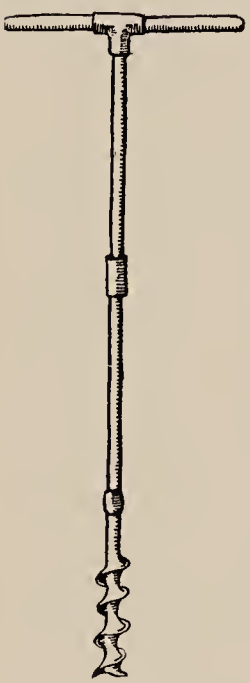


FIG. 52.—Auger used in the field examination of soil and in taking samples. Note modified cutting edge.

The method for estimating the soil humus, although it is not a bulk method, should be considered at this point because of its close relationship to the determination of organic carbon. The modified Grandeau procedure (par. 61) is used for humus estimation and is supposed to distinguish between the more active and less active organic matter. Of the two methods the determination of organic carbon is by far the more accurate. As there is also some doubt about the comparative activity of the material extracted by the Grandeau procedure the figure for organic carbon seems in general the more significant and it is the determination usually made. The estimation of soil humus may, therefore, be considered as a chemical method of secondary importance except in special cases.

The total nitrogen of the soil is determined by either the Kjeldahl, the modified Kjeldahl, or by the Gunning method. The determination of nitrogen is such a common laboratory

is obtained. Where large areas are involved, as in the case of a soil survey, only one sample, representative of the soil type being studied, is usually taken.

procedure that it is worth while to consider the principles involved.[1] About 10 grams of dry soil are placed in a Kjeldahl flask with about 30 c.c. of strong sulfuric acid and 0.7 gram of mercuric oxide or its equivalent in metallic mercury. The mixture is boiled vigorously until the solution is clear. The flask is then removed from the flame and, while hot, potassium permanganate is added in small quantities to complete the oxidation until, after shaking, the liquid remains a green or purple color. The nitrogen of the soil, no matter what has been its combination, is now in the form of ammonium sulfate $[(NH_4)_2SO_4]$, the mercury acting as a catalytic agent and the permanganate as an oxidizer.

After cooling, the contents of the flask are diluted with about 200 c.c. of water, zinc dust or a few pieces of granulated zinc are added to prevent bumping and 25 c.c. of potassium sulfid are poured in with shaking. Next a sodium hydroxide solution, suffcient in amount to neutralize the acid, is carefully poured down the side of the flask. The flask is then connected with a condenser and the contents cautiously mixed by shaking. The ammonia set free by the alkali is distilled over into a standard acid, the excess acid being titrated with a standard alkali, using a suitable indicator. When the amount of standard acid neutralized is known, the amount of nitrogen, which has passed over in the form of ammonia, may be calculated and expressed as a percentage, based on the original dry sample of soil. (See Fig. 53.)

[1] The method described above is the Kjeldahl method. See *Official and Tentative Methods of Analysis of the Assoc. Official Agr. Chemists,* p. 314, 1920.

This method does not determine the nitrogen in the nitrate form. If this is desired a modified procedure must be followed. As the nitrate nitrogen in most soil is low compared to the nitrogen in other combinations, the objection just made to the regular Kjeldahl method is not serious.

Snyder, R. S., *Determination of Total Nitrogen in Soils Containing Rather Large Amounts of Nitrates;* Soil Sci., Vol. VI, No. 6, pp. 487-490, 1918.

166. Bulk analysis—complete solution of the soil.—By the use of hydrofluoric acid or by fusion with potassium and sodium carbonate, the entire soil mass may be decomposed and

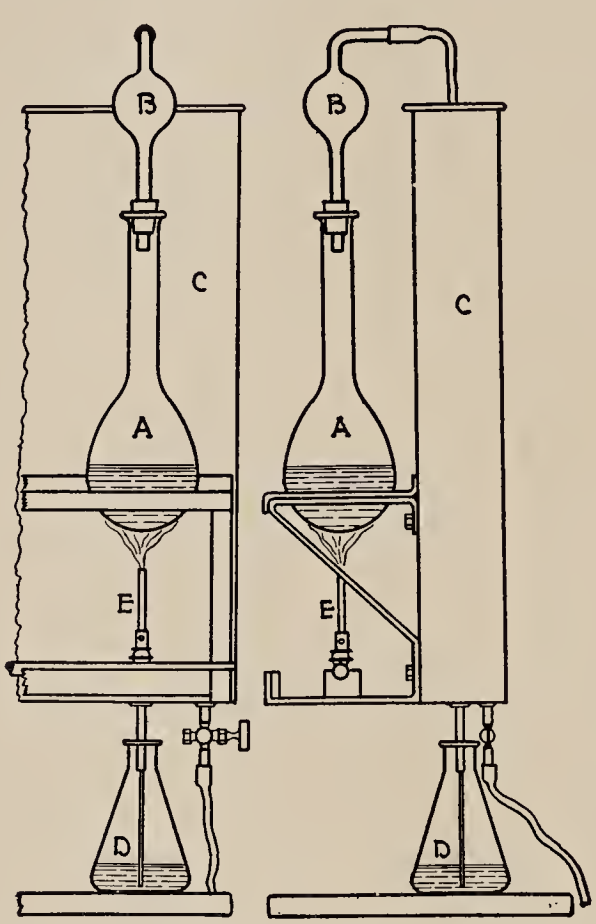


FIG. 53.—Front and side view of a Kjeldahl distilling battery. (A), Kjeldahl flask; (B), trap; (C), condenser tank; (D), receiving flask containing standard acid and (E), Bunsen burner.

its constituents determined.[1] The amount of lime (CaO) or any other constituent,[2] may thus be expressed in percentage

[1] Wiley, Harvey W., *Principles and Practices of Agricultural Chemical Analysis*, Vol. 1, pp. 398-399, 1906.

[2] Schollenberger presents some interesting data regarding the pro-

based on dry soil or in pounds to the acre to any suitable depth. This method gives only the total of any constituent and tells nothing regarding its availability to crops, although a marked deficiency in any element may thus be detected. A rock will often show greater amounts of the mineral elements than a fertile soil.[1]

167. Partial analysis of the soil for mineral constituents.—When it was realized that a bulk analysis of the soil, especially for the mineral constituents, gave no information as to the availability of certain elements or as to the fertilizer needs of the soil, extraction methods were devised. Such methods, of whatever character they may be, are designed to

portion of organic and inorganic phosphorus in Ohio soils. The figures are an average of twelve types.

Soils	Total P_2O_5	Organic P_2O_5 as per cent of total	Total N
	%	%	%
Cultivated			
0- 7 inches	.0433	34	.14
7-15 inches	.0345	20	.07
Virgin			
0- 7 inches	.0587	24	.19
7-15 inches	.0381	21	.08

Schollenberger, C. J., *Organic Phosphorus Content of Ohio Soils;* Soil Sci., Vol. X. No. 2, pp. 127-141, 1920.

For methods of determining organic phosphorus, see Potter, R. S., *The Organic Phosphorus of Soil;* Soil Sci., Vol. II, No. 4, pp. 291-298, 1916.

Rost, C. O., *The Determination of Soil Phosphorus;* Soil Sci., Vol. IV, No. 4, pp. 295-311, 1917.

Potter, R. S., and Snyder, R. S., *The Organic Phosphorus of Soil;* Soil Sci., Vol. VI, No. 5, pp. 321-332, 1918.

Schollenberger, C. J., *Organic Phosphorus of Soil: Experimental Work on Methods for Extraction and Determination;* Soil Sci., Vol. VI, No. 5, pp. 365-395, 1918.

[1] Sulfur is determined by a separate method. *Official and Tentative Methods of Analysis of the Assoc. of Official Agr. Chemists,* p. 317, 1920.

See also, Hart, E. B., and Peterson, W. H., *Sulphur Requirements of Farm Crops in Relation to the Soil and Air Supply;* Wis. Agr. Exp. Sta., Res. Bul. 14, 1911.

give information regarding the availability of the plant nutrients within the soil. They may be listed under three heads: (1) digestion with strong acids, (2) digestion with dilute acids, and (3) extraction with water. These methods will be discussed in the order mentioned.

168. Digestion with strong acids.—While surfuric, nitric, and hydrochloric acids have all been used as solvents,[1] the one most commonly employed is hydrochloric acid of 1.115 specific gravity.[2] It has been used to such an extent that it may be considered the standard solvent, and a statement of a chemical analysis of a soil in this country may be considered as based on this solvent unless otherwise stated.

An analysis by this method is supposed to show the proportion of nutrient materials in a soil that is in a condition to be used ultimately by plants at the time when the analysis is made. The nutrient materials that are not dissolved by treatment with hydrochloric acid are assumed to be in a condition in whch plants cannot use them. The difficulty with this assumption is that, while treatment with hydrochloric acid of a given strength marks a definite point in the solubility of the compounds in the soil, it does not bear a uniform relation to the natural processes by which these compounds become available to plants.

This method is not only arbitrary but it is artificial as well.

[1] The following analyses of the same soil quoted from Snyder are interesting in this regard. Snyder, H., *Soils;* Minn. Agr. Exp. Sta., Bul. 41, p. 66, 1895.

Extract	Total	K_2O	CaO	MgO	P_2O_5	SO_3
	%	%	%	%	%	%
HCl	18.80	.42	.55	.40	.23	.08
HNO_3	16.55	.30	.30	.32	.23	.08
H_2SO_4	19.55	.52	.53	.52	.26	.10

[2] *Official and Provisional Methods of Analysis;* U. S. Dept. Agr., Bur. Chem., Bul. 107 (revised), pp. 14-18, 1908.

While it is supposed to measure the permanent fertility [1] of a soil, there is no reason to suppose that there is any relationship between the nutrients extracted by a strong acid in the laboratory and the amounts of the same constituents absorbed by crops over a period of fifty or one hundred years. Moreover, productivity is not necessarily controlled by the amounts of available nutrients in a soil. This further vitiates the data obtained by such an analysis.

Snyder [2] has analyzed a number of Minnesota soils by means of digestion with strong hydrochloric acid, decomposing the acid-insoluble residues by fusion and determining their composition. Veitch [3] has analyzed certain Maryland soils by the hydrochloric acid method and by means of complete solution. A few examples are given below to show how soils may vary in the solubility of their constituents in strong hydrochloric acid:

TABLE LXX

PERCENTAGE OF SOIL CONSTITUENTS INSOLUBLE IN HCl, SP. GR. 1.115

SOILS	K_2O	CaO	MgO	P_2O_5	SO_3
Minnesota (Snyder)					
Fair Haven	94	25	58	40	74
Holden	81	61	76	45	90
Experiment Station	83	41	36	18	20
Maryland (Veitch)					
Columbia	95	90	34	66	—
Chesapeake	67	82	29	15	—
Hudson River Shale	73	37	28	0	—

169. Digestion with dilute acids.—A great number of different acids have been used in a dilute condition for ex-

[1] Fertility is used here in the sense of potential productivity, the nutrients in the soil being considered as the controlling factor.

[2] Snyder, Harry, *Soils;* Minn. Agr. Exp. Sta., Bul. 41, p. 35, 1895.

[3] Veitch, F. P., *The Chemical Composition of Maryland Soils;* Md. Agr. Exp. Sta., Bul. 70, p. 103, 1901.

tracting soils, the idea being in every case to determine the amount of the mineral nutrients immediately available to crops. The scope is thus narrower than in the digestion with strong acids, by which the permanent fertility is sought.

Two acids have been commonly utilized in the extraction of soils with dilute solvents: one per cent. citric acid proposed by Dyer,[1] and one-fifth normal nitric acid.[2] Dyer adopted the one-per-cent. strength as the result of an investigation in which he determined the acidity of the juices in the roots of over one hundred species or varieties of plants representing twenty different natural orders. The implication is that plants produce a solvent action on a soil in proportion to the acidity of their juices, but an examination of Dyer's figures does not show that the size of the crop ordinarily produced by the plants would in many cases correspond to the acidity of their juices. Thus, of the Cruciferæ, the horse-radish has several times the acidity of the Swedish turnip or of the field cabbage, although the crop produced by the former is much less than that of the latter two.

Dyer's method gave results on Rothamsted soils that enabled him to estimate their relative productivity. On other soils and in the hands of other investigators, however, the method is unsatisfactory. In soils rich in calcium and low in iron and aluminum, it may often show the amounts of easily soluble phosphoric acid and potash.

In ease of manipulation, the fifth normal nitric acid is preferable to the one-per-cent. citric acid, which is rather tedious to work with. It has been utilized nearly as extensively in this country as has the latter in Great Britain. Its use has been confined largely to the determination of the readily available phosphoric acid and potash in the soil, as

[1] Dyer, Bernard, *On the Analytical Determination of Probably Available "Mineral" Plant Food in Soils;* Jour. Chem. Soc., Vol. LXV, pp. 115-167, 1894.

[2] *Official and Provisional Methods of Analysis;* U. S. Dept. Agr., Bur. Chem., Bul. 107 (revised), p. 18, 1908.

has the citric acid method. It is obvious that some materials are more readily soluble than others, and for that reason the method will distinguish between phosphorus and potassium in different forms. The calcium phosphates are supposed to be entirely soluble in this strength of acid. According to Fraps,[1] it dissolves iron and aluminum phosphates to only a slight extent, thus distinguishing between these forms of phosphorus and calcium phosphate. Fraps finds also that no potassium is removed from orthoclase and microcline, that less than 10 per cent. is dissolved from glauconite and biotite, and that from 15 to 60 per cent. is dissolved from muscovite, nephelite, leucite, apophyllite, and phillipsite, minerals known to be rather easily available.

There are several factors, however, that make the use of one-fifth normal nitric acid an uncertain guide to the available phosphoric acid and potash in the soil. When a soil is treated with the acid, some of it is neutralized by the reactions that result and thus its strength is lessened. This may have no relation to the quantities of phosphoric acid or potash dissolved. Some analysts correct for the neutralization and some do not. Again, as with concentrated hydrochloric acid, the degree of solubility of the soil constituents in the nitric acid may not correspond with the ability of the plant to obtain these substances. With this, as with the other methods discussed, the objection holds that the results cannot be taken as an infallible guide to the productiveness of a soil, or to its fertilizer needs. The artificial extraction of a soil in the laboratory cannot be expected to simulate the action of a crop even for one year.

170. Extraction with water.—As carbon dioxide is a universal constituent of the water of the soil, and without

[1] Fraps, G. S., *Active Phosphoric Acid and Its Relation to the Needs of the Soil for Phosphoric Acid in Pot Experiments;* Tex. Agr. Exp. Sta., Bul. 126, pp. 7-72, 1909.

Also, *The Active Potash of the Soil and Its Relation to Pot Experiments;* Tex. Agr. Exp. Sta., Bul. 145, pp. 5-39, 1912.

doubt a potent factor in the decomposition of the mineral matter, it has been proposed to use a solution of carbon dioxide as a solvent in soil analysis. The amounts of soil constituents taken up by this solvent are much less than are taken up by any of the others heretofore mentioned, but all mineral substances used by plants are soluble in it to some extent. The amount of phosphoric acid is so small as to make its detection by the gravimetric method difficult. Like other methods employing very weak solvents, this is open to the objection that much of the material dissolved cannot be removed because of the absorptive power of the soil, and as this varies with the character of the soil, adequate comparisons cannot be made. Water charged with carbon dioxide has been very largely replaced by pure water in making such extractions.

When soil is digested with distilled water, all the mineral substances used by plants are dissolved from it, but in very small quantities. It has been proposed to employ this extract for soil analysis on the ground that it is a natural solvent and dissolves only those nutrients in a condition to be used by plants. By determining the moisture content of the soil and using a known quantity of water for the extraction, the parts per million of the extracted nutrients may be expressed on the basis of the dry soil or of the solution. The aqueous extract does not by any means contain the entire quantity of nutrients which were in the soil solution and is not an exact measure of the fertility in this form. Absorption holds back an undetermined and variable quantity of the important constituents and thus vitiates the method, especally for comparing different soils. The method, however, is very valuable for comparing the same soil at different times, especially as regards the nitrates. The nitrate radical is not absorbed to any great degree by the soil and presents a very fair measure of the concentration of the soil solution as far as this constituent is concerned.

The water extract method generally followed in this country is that established by the Bureau of Soils. One hundred grams of soil are mixed with 500 cubic centimeters of water and stirred for three minutes. After standing twenty minutes the supernatant liquid is filtered through a Pasteur-Chamberland filter under pressure. It is then ready for analysis. Colometric and turbidity methods are usually employed in determining the amounts of the constituents removed.[1] The method is of greatest use in estimating the nitrate content of soils.

The quantity of extracted material depends on the absorptive properties of the soil, on the amount of water used in the extraction, and on the number of extractions. Analyses of the aqueous extract of a clay and of a sandy soil from the Cornell University farm serve to illustrate the greater retentive power of the former for nitrates. Sodium nitrate was applied to a clay soil and to a sandy loam soil at the rate of 640 pounds to the acre. Analyses of aqueous extracts some ninety days later showed the following:

TABLE LXXI

KIND OF SOIL	FERTILIZER	NITRATES IN SOIL (Parts per million)
Clay	Sodium nitrate	7.8
Clay	No fertilizer	1.8
Sandy loam	Sodium nitrate	150.0
Sandy loam	No fertilizer	29.7

There was apparently a much greater retention of nitrate by the clay soil, as shown by a comparison of the fertilized and unfertilized plats on both soils.

[1] Schreiner, O., and Failyer, G. H., *Colorimetric, Turbidity and Titration Methods Used in Soil Investigations;* U. S. Dept. Agr., Bur. Soils, Bul. 31, 1906.

Schulze [1] extracted a rich soil by slowly leaching one kilo with pure water, one liter of water passing through in twenty-four hours. The extract for each twenty-four hours was analyzed every day for a period of six days. The total amounts dissolved during each period were as follows:

TABLE LXXII

SUCCESSIVE EXTRACTION	TOTAL MATTER DISSOLVED GRAMS	VOLATILE GRAMS	INORGANIC GRAMS
First	.535	.340	.195
Second	.120	.057	.063
Third	.261	.101	.160
Fourth	.203	.083	.120
Fifth	.260	.082	.178
Sixth	.200	.077	.123

It will be noticed that the dissolved matter, both organic and inorganic, fell off markedly after the first extraction. Later extractions were doubtless supplied largely from the substances held by absorption, which gradually diffused into the water extract as the tendency to maintain equilibrium of the solution overcame the absorptive action. With the removal of the absorbed substances the equilibrium between the absorption and solution surfaces and the surrounding solution is disturbed, diffusion and solution are increased, and more material gradually passes from the soil into the solution. In this way, a more or less uniform and continuous extraction is mantained.

In spite of the obvious defects of the water extraction method the work of Hoagland, Burd and Stewart [2] seems to indicate that such data, if obtained over an extended period,

[1] Schulze, F., *Über den Phosphorsaure-Gehalt des Wasser-Auszugs der Ackererde;* Landw. Vers. Stat., Band 6, Seite 409-412, 1864.

[2] Burd, J. S., *Water Extractions of Soils as a Criteria of their Crop-*

are a good comparative measure of the concentration and composition of the soil solution (see par. 145). They also consider water extractions as criteria of the crop-producing power of a soil so studied. The practical value of such a method as a means of estimating fertility is, however, somewhat questionable, since much time and labor are required to make the necessary extractions and analyses before conclusions at all reliable may be drawn.

171. Fertility evaluation by means of chemical analyses. —The important part that chemistry plays in soil investigation and research should not be overlooked. Nor can a satisfactory presentation of soil phenomena, whether with a technical or an applied bearing, be made without the use of some chemistry. Chemistry, in fact, is the fundamental science that is most utilized in soil study.

In spite of these relationships, the value of chemistry in the direct solution of practical fertility problems is neither absolute nor final. The objections already raised to the digestion of the soil, either with concentrated or dilute acids, shows the inadequacy of these methods so far as practical problems are concerned.

Of all the chemical analyses discussed those that have to do with the determination of organic carbon, total nitrogen, total calcium and phosphoric acid are of outstanding value. Organic matter is such an important soil constituent that a knowledge of its amount cannot fail to throw much light on the physical and chemical condition of the soil. Much of the soil nitrogen is carried by the organic matter and becomes available in much larger proportion than do the mineral nutrients. An analysis for total nitrogen is, therefore, a

Producing Power; Jour. Agr. Res., Vol. XII, No. 6, pp. 297-309, 1918.

Stewart, G. R., *Effect of Season and Crop Growth in Modifying the Soil Extract;* Jour. Agr. Res., Vol. XII, No. 6, pp. 311-368, 1918.

Hoagland, D. R., *The Freezing Point Method as an Index of Variations in the Soil Solution Due to Season and Crop;* Jour. Agr. Res., Vol. XII, No. 6, pp. 369-395, 1918.

fairly reliable guide in some cases to the fertility of the soil under specific consideration.

Although the relationship of organic matter and nitrogen to soil fertility is so close that certain generalized tables [1] may be cited for the interpretation of chemical data, no close correlation is possible, especially where soils of markedly different character are compared. So many other factors may enter that practically no opinion can be formed regarding the productivity of a soil unless other and more detailed data are available.

An interesting example of where the nitrogen content fails to indicate the relative fertility of two soils is found in certain unpublished data from the Cornell Agricultural Experiment Station. Two soils are being studied in the lysimeter tanks—Dunkirk silty clay loam and Volusia silt loam. In Table LXXIII is given the nitrogen and calcium content of these soils and the pounds of nitrogen removed to the acre by maize, oats, and barley, respectively, for the years 1915, 1916, and 1917. The treatment and handling of the soils compared has been the same.

While the nitrogen, phosphoric acid and potash contents of these soils are about the same, a marked difference is noted in their productivity. This may be due, at least partially, to the calcium content, which is rather high in the Dunkirk, especially in the subsoil. In comparing soils over wide areas

[1] The following tentative classification of soils on the basis of their percentages of organic matter and nitrogen is offered for generalized field use:

Description	Percentage of Organic Matter	Percentage of Nitrogen
Low	.0- 3.0	.00- .10
Medium	3.0- 6.0	.10- .25
High	6.0-10.0	.25- .40
Very high	above 10.0	above .40

TABLE LXXIII

THE PERCENTAGES OF NITROGEN AND CALCIUM IN THE DUNKIRK SILTY CLAY LOAM AND THE VOLUSIA SILT LOAM AND THE NITROGEN REMOVED BY CERTAIN CROPS. CORNELL LYSIMETER TANKS.

SOILS	CaO %	N %	POUNDS OF N REMOVED PER ACRE		
			MAIZE 1915	OATS 1916	BARLEY 1917
Dunkirk silty clay loam...			53.6	62.3	44.0
First foot.....	.340	.134			
Second foot.....	.280	.062			
Third foot.....	.490	.064			
Fourth foot.....	1.530	.054			
Volusia silt loam.....			28.3	21.7	18.8
First foot.....	.230	.145			
Second foot.....	.165	.052			
Third foot.....	.260	.059			
Fourth foot.....	.365	.050			

and in a general way there is often some correlation between the amount of calcium present and the productivity. In humid regions soils high in lime are usually fertile. Within certain limits, therefore, calcium becomes significant in fertility studies.[1]

Some idea concerning the relative value of the various chemical methods, especially those dealing with potash, lime, phosphoric acid, and magnesia, may perhaps be obtained by comparing actual data. Burd [2] has analyzed a number of soils,

[1] Shedd, O. M., *A Proposed Method for the Estimation of Total Calcium in Soils and the Significance of this Element in Soil Fertility;* Soil Sci., Vol. X, No. 1, pp. 1-14, 1920.

[2] Burd, J. S., *Chemical Criteria, Crop Production and Physical Classification in Two Soil Classes;* Soil Sci., Vol. V, No. 6, pp. 405-419, 1918.

some good, some poor, by several different methods. Representative figures are given below:

TABLE LXXIV

CHEMICAL COMPOSITION OF A GOOD AND A POOR SOIL AS INDICATED BY SEVERAL DIFFERENT METHODS

CONDITIONS	PERCENTAGE OF			
	K_2O	CaO	MgO	P_2O_5
Bulk analysis				
Productive silt loam.....	1.98	1.48	2.66	.23
Unproductive silt loam.....	1.85	1.50	3.57	.21
Concentrated HCl digestion				
Productive silt loam.....	1.05	1.43	2.46	.22
Unproductive silt loam.....	.89	1.48	3.32	.20
One per cent. citric acid				
Productive silt loam.....	.039	.452	.220	.101
Unproductive silt loam.....	.039	.422	.144	.072
Water extract	p.p.m.	p.p.m.	p.p.m.	p.p.m.
Productive silt loam.....	57	127	40	12
Unproductive silt loam.....	52	45	23	5

A comparison of the figures from the good and poor soil seems to indicate no differences large enough to warrant opinions regarding their relative fertility, except in the case of the water extracts. These latter figures, however, are seasonal averages and required as long a time to procure as was necessary to grow a crop. Such fertility measurement is not as practicable as actually using the crop as an indicator.

172. Resume.—The conclusion that chemical analyses are of but little direct practical value as a guide to soil productivity is unavoidable. In spite of the great importance of chemistry in research and teaching, it fails to indicate either the permanent or the immediate fertility of the land. No chemical method is capable of showing substantial and constant differences between soils producing within 20 per cent.

of each other. Even if an analysis should show the nutrients, which would be available over a term of years, it would still be inadequate, since available nutrients are only one of a great number of factors which govern productivity.[1] This productivity equation may be indicated as follows:

Productivity = Texture × structure × organic matter × moisture × available nutrients × soil reaction × weather × plant disease × care of farmer, etc., etc.

The factors of this equation are variables, their importance in determining productivity depending on many things. An accurate knowledge of the available soil nutrients, even if procurable, would aid but little in solving such an equation.

The solution of individual or community fertility problems is best accomplished by the aid of experienced and technically trained men, who understand the scientific principles underlying the common field procedures and who also are in touch with the experiences of farmers over wide and diverse areas. Such men may advise not only in regard to the crops that should be grown but also as to their rotation, management, and fertilization from seeding until harvest. These men may also institute such coöperative experiments and tests as will best throw light on fertility problems untouched by practical experience.

[1] The samples sent to a chemical laboratory by farmers are generally improperly taken and consequently are not representative. It would be unwise to analyze such soils even if the methods were capable of showing all that could be wished for.

CHAPTER XVII

ALKALI SOILS[1]

It has already been shown that soils are acted on by a great variety of weathering agents which gradually render soluble a portion of the most susceptible constituents. This soluble material becomes a part of the soil solution and may come in contact with the roots of any crop growing on the land. In humid regions, where a large quantity of water percolates through the soil, this soluble matter has little opportunity to accumulate.[2] In arid regions, however, where loss by drainage is slight, these salts may often collect in large amounts. During periods of dry weather they are carried upward by the capillary rise of the soil-water, while during periods of rainfall they may move downward again in proportion to the leaching action. At one time the lower soil may contain considerably more soluble salt than the upper; at another time the condition may be reversed, in which case the solution in contact with roots may contain so much soluble matter that vegetation is injured or destroyed. This excess of soluble salts usually has a marked alkaline reaction, but in any case it produces what is termed an *alkali soil.*

Large areas of land in every continent carry soluble salts to such an extent that alkali injury is either actual or poten-

[1] For a complete and satisfactory treatise on alkali see Harris, F. S., *Soil Alkali,* New York, 1920.

[2] Peat soils in humid regions may sometimes contain high concentrations of salts, commonly non-toxic, and lower concentrations of extremely toxic salts.

Conner, S. D., *Excess Soluble Salts in Humid Soils;* Jour. Amer. Soc. Agron., Vol. 9, No. 6, pp. 297-301, 1917.

tial. It is estimated that 13 per cent. of the irrigated land of the United States contains sufficient soluble salts seriously to interfere with crop growth. This alone amounts to nine million acres and does not include the millions of acres not under the ditch that are affected to a marked degree by alkali. Similar figures are available from other continents and, since alkali conditions can be alleviated and controlled to a certain extent, the importance of the subject becomes apparent.

Entirely aside from the economic aspects, alkali is of great interest scientifically, offering a research field of such range and complexity as to involve many sciences. A greater portion of the practical information regarding alkali and its control has arisen from the purely scientific interest that has been directed towards this peculiar soil condition.

173. Composition of alkali.—It has been emphasized previously that the solution of a normal humid-region soil is of such dilution as to be largely ionic in character except in periods of low moisture content. In a soil affected with alkali it is obvious that the molecular state is dominant and that certain salts may exist and function as definite entities. Thus the following bases may be expected to be present—sodium, potassium, magnesium, calcium, and sometimes ammonium. The common acid radicals are chlorides, sulphates, carbonates, bicarbonates, phosphates, and nitrates. The salts that are present and their proportion not only in the soil solution but as a precipitant will vary with conditions.

The following table indicates not only the salts that may be present but the composition of the alkali as reported by a number of different investigators. (See table LXXV, p. 330.)

174. White and black alkali.—Sulfates and chlorides of the alkalies, when concentrated on the surface of the soil, produce a white incrustation, which is very common in alkali regions during a dry period as a result of the evaporation of moisture. Incrustations of this character are called *white alkali.*

Table LXXV

COMPARISON OF ALKALI EXPRESSED IN PERCENTAGE OF THE DIFFERENT SALTS PRESENT.

Salt	Colorado Exp. Sta.[1]	California (Tulare) Exp. Sta.[2]	Yakima,[3] Wash. 12-24 Inches	Billings, Mont.[3]		Yuma, Ariz.[3]	
				Crust	Surface 10 Inches	Crust	0-72 Inches
KCl	1.6	—	5.6	—	—	4.0	22.0
K_2SO_4	—	3.9	—	1.6	21.4	—	—
K_2CO_3	—	—	9.7	—	—	—	—
Na_2SO_4	—	25.3	—	85.6	35.1	—	—
$NaNO_3$	33.1	19.8	—	—	—	—	—
Na_2CO_3	—	32.6	13.8	—	7.3	—	—
$NaCl$	6.6	14.7	—	.5	—	81.1	13.7
Na_2HPO_4	—	2.2	—	—	—	—	—
$MgSO_4$	—	—	—	8.9	4.0	—	6.9
$MgCl_2$	12.7	—	—	—	—	7.7	4.0
$CaCl_2$	17.3	—	—	—	—	.2	—
$NaHCO_3$	—	—	36.7	.6	22.0	.3	21.0
$CaSO_4$	21.5	—	1.9	2.7	10.0	6.6	32.2
$Ca(HCO_3)_2$	—	—	16.5	—	—	—	—
$Mg(HCO_3)_2$	—	—	15.7	—	—	—	—
$(NH_4)_2CO_3$	—	1.4	—	—	—	—	—

Carbonates of the alkalies, particularly sodium carbonate, dissolve organic matter from the soil, thus giving a dark color to the solution and to the incrustation. For this reason, alkali containing large quantities of these salts is called *black alkali.* Black or brown alkali may also be produced by calcium chloride or by an excess of sodium nitrate.

Black alkali is much more destructive to vegetation than is the white. A quantity of the latter which would not seriously

[1] Headden, W. P., *The Fixation of Nitrogen;* Colo. Agr. Exp. Sta., Bul. 155, p. 10, 1910.

[2] Hilgard, E. W., *Soils,* p. 442, New York, 1906.

[3] Dorsey, C. W., *Alkali Soils of the United States;* U. S. Dept. Agr., Bur. Soils, Bul. 35, 1906.

interfere with the growth of most crops might completely prevent the development of useful plants if the alkali were black.

175. Origin of alkali.—While the presence of alkali and its influence on plants has been known for centuries, it is only within recent years that its probable mode of origin has been understood. The soluble salts have undoubtedly come from the materials which have formed the soils, the reactions being as complex as the ordinary transformations which take place in soil formation.

Some soils have been laid down as deltas in arms of the ocean. If these bodies of water later are cut off from the sea and gradually dry up under arid conditions, an alkali soil will be left. In a similar way saline lakes may disappear and soils heavily charged with alkali will result.

The commonest mode of origin for alkali soil is through ordinary weathering under conditions of aridity. Almost any rock will give rise to soils rich in alkali salts if leaching is not a feature in the weathering processes. In western United States the origin of much of the soil affected to the greatest degree with alkali is associated with strata originally carrying much soluble material. When such rock forms soil, the alkali arises not only from the decomposition of the minerals of which the rock is composed, but is greatly reinforced by the soluble salts already present. The Cretaceous and Tertiary beds in Utah, Colorado, and Wyoming are of this character, having been laid down in brackish water. They naturally give rise to soils high in alkali.[1]

One fact that is often overlooked in practice is that the amount of alkali in the surface layers of soil may be greatly increased by improper handling. Rapid evaporation after rain or irrigation will carry the soluble salts toward the surface and deposit them near to or in the root zone. Again, over-irriga-

[1] Stewart, R., and Peterson, W., *Origin of Alkali;* Jour. Agr. Res., Vol. X, No. 7, pp. 331-353, 1917. See also, Breazeale, J. F., *Formation of Black Alkali in Calcareous Soils;* Jour. Agr. Res., Vol. X, No. 11, pp. 541-589, 1917.

tion may produce leaching into lower lands, an alkali condition generally resulting if the areas so affected remain water-logged for a long time.

Very often alkali is localized in small areas called *alkali spots.* These vary in size from a few square yards to several acres. In years of good rainfall these areas may be productive, but in dry years they are often quite sterile. Their origin is generally due to seepage, the ground water being near enough the surface to allow a concentration of salts by capillarity, especially in dry seasons.

A very peculiar type of alkali spot occurs in the Grand Valley of Colorado and elsewhere, the predominant salt being the nitrate, which does not usually occur in large amounts as alkali. Two theories have been advanced to account for the presence of the nitrate salts. One hypothesis [1] is that the surrounding shales are comparatively rich in nitrates and that the alkali accumulation is a leaching and seepage process. The other theory is biological in nature.[2] Such soils are capable of rapid nitrogen fixation by means of their bacterial flora. The idea is advanced that the nitrogen is fixed from the air very rapidly in these spots and later oxidized to the nitrate form. Whatever the origin of the soluble salts the fact remains that such spots are quite destructive, spreading very rapidly until whole orchards are wiped out.

Water used for irrigation is very often heavily charged with alkali, especially where any amount of the water previously applied to the soil finds its way back into the streams. At Canon City, Colorado, the Arkansas River is very pure. At a point 120 miles below the soluble salts have been known

[1] Stewart, R., and Peterson, W., *The Nitric Nitrogen Content of the Country Rock;* Utah Agr. Exp. Sta., Bul. 134, 1914.

Also, *Further Studies of the Nitric Nitrogen Content of the Country Rock;* Utah Agr. Exp. Sta., Bul. 150, 1917.

[2] Headden, W. P., *The Fixation of Nitrogen in Colorado Soils;* Colo. Agr. Exp. Sta., Bul. 186, 1913.

Sackett, W. G., and Isham, R. M., *Origin of the Niter Spots in Certain Western Soils;* Science, N. S., Vol. 42, pp. 452-453, 1915.

to reach a concentration of 2200 parts per million. The quantity of soluble salts that may be present in irrigation water before it is unfit for use depends on certain conditions. This amount will vary with the crop, the rainfall, the soil, the composition of the alkali, and a number of other factors.

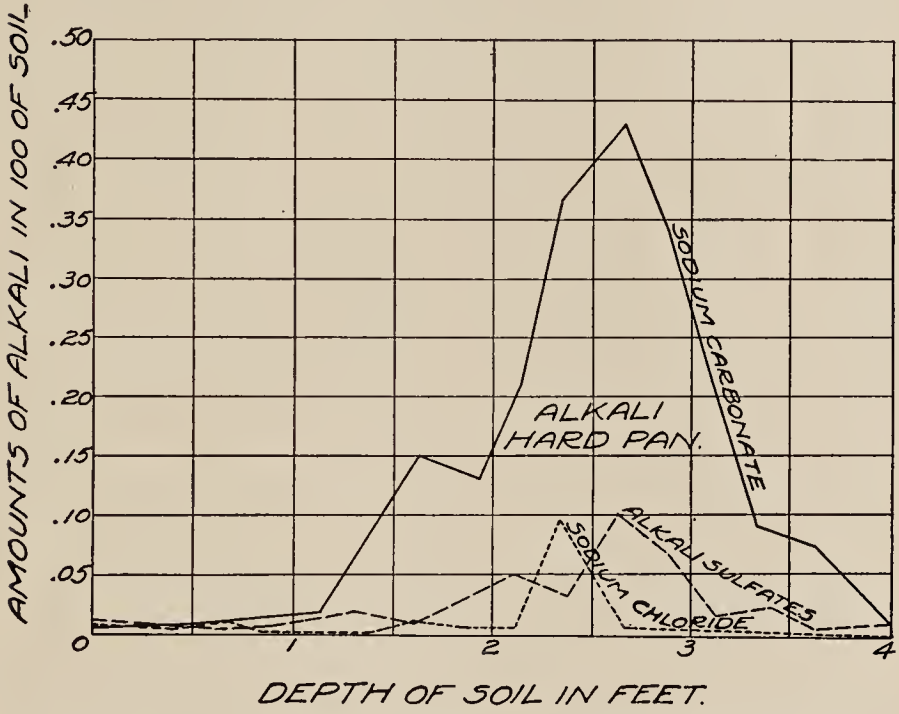


FIG. 54.—Diagram showing the amount and composition of alkali salts at various depths in a soil at Tulare, California. (After Hilgard.)

Where the alkali is of the sodium sulfate type rather high concentrations are admissible, running as high as 1000 parts per million. Water carrying black alkali must be used with great caution. Table LXXVI indicates the concentration that may be expected in normal irrigation water.

The preponderance of sodium chloride is almost always a feature, not only in alkali water but also in soils affected with alkali salts. This may be explained as due to differential ab-

TABLE LXXVI

ANALYSIS OF SOME TYPICAL ALKALINE RIVER WATER OF WESTERN UNITED STATES.[1]

STREAM	TOTAL SOLIDS	PERCENTAGE OF TOTAL SOLIDS AS							
	p.p.m.	Cl	SO_4	CO_3	Na	K	Ca	Mg	SiO_2
Malad River, Utah	4,395	50.0	2.9	4.7	37.4	...	....	...	...
Sevier River at Delta, Utah	1,316	25.0	24.1	17.9	16.4	...	5.3	6.5	...
Rio Grande, Texas	791	21.6	30.1	11.5	14.8	.8	13.7	3.0	3.8
Mill Creek, Montana ..	3,747	7.4	17.3	35.1	23.5	1.4	10.1	2.2	.7
San Benito, California.	936	13.8	29.0	38.3	13.1	5.4	6.6	7.7	2.6
Buckeye Canal, Arizona	1,972	39.9	7.3	9.6	24.9	.6	6.6	2.9	2.7

sorption of ions by the soil. Sodium and chlorine ions seem to be about as little absorbed by the soil as any of the common soil constituents. They are thus readily carried through the soil and are free to accumulate in considerable amounts at points where they may become noticeable. Their union of necessity produces large quantities of sodium chloride or common salt.[2]

176. Effect of alkali on crops.—The presence of relatively large amounts of salts dissolved in water and brought into contact with a plant cell has been shown to cause a shrinkage of the protoplasmic lining of the cell. This action, called *plasmolysis,* increases with the concentration of the solution until the plant finally dies. The phenomenon is due to the osmotic movement of the water, which passes from the cell towards the more concentrated soil solution. The nature of the salt, the species, and even the individuality of the plant, as well as other factors, determine the exact concentration at which the plant succumbs. The carbonates of the alkali bases have, in addition, a corroding effect on the plant tissues, dis-

[1] Harris, F. S., *Soil Alkali,* p. 232; New York, 1920.

[2] Dorsey, C. W., *Alkali Soils of the United States;* U. S. Dept. Agr., Bur. Soils, Bul. 35, 1906.

solving the parts of the plant with which they come into contact. Such action is not as important as plasmolysis and when it does occur is most noticeable at the root crown. (See Fig. 55.)

Indirectly, alkali may influence plants by its effect on soil tilth, soil organisms, and fungous and bacterial growths. Marchal,[1] for example, found that the formation of nodules, containing the nitrogen-fixing organisms, did not develop well

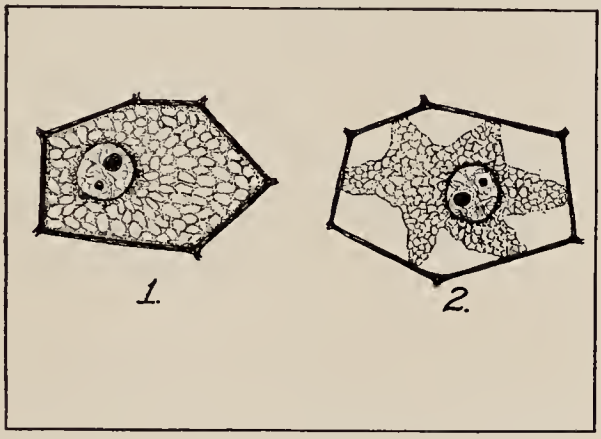


FIG. 55.—(1) Cross-section diagram of a normal plant cell. (2) Cell after plasmolysis has taken place.

on pea roots in nutrient solutions when certain concentrations of salts were maintained. Ammonium salts were injurious at a concentration of 500 parts per million. Potassium and sodium salts retarded the nodule development at 5000 and 3333 parts to the million respectively. The quantity of alkali that will cause injury to ammonifying and nitrifying bacteria varies from 250 to 4000 parts per million, depending on conditions.

177. Resistance of different plants to alkali.—The factors that determine the tolerance of plants toward alkali are:

[1] Marchal, E., *Influence des Sels minéraux nutritifs sur la Production des nodosités chez le Pois;* Compt. Rend. Acad. Sci. (Paris), Tome 133, No. 24, p. 1032, 1901.

(1) the physiological constitution of the plant, and (2) the rooting habit. The former is little understood, so much depending on the character of the alkali solution, the nature of the cell-wall, and the character and activity of the cell contents. It has long been known that the toxicity of two salts when together is considerably less than the sum of their detrimental action when used alone. This ameliorating or antagonistic action varies for different salts, seeming to be greatest when calcium and magnesium are involved. This is but an example of the complexities which arise when an attempt is made to study the physiological relationships of alkali injury.

The rooting habit of plants in their relation to alkali tolerance is more easily understood. The advantage is always with deep-rooted crops, such as alfalfa and sugar-beets, probably because a portion of the root may be in a less strongly impregnated part of the soil.

The tolerance of many plants to alkali has been studied in water culture. Such results are not of great practical value, however, as it is only in soil that all of the numerous factors, such as absorption, antagonism, and physical conditions, come into play. Harris and Pittman [1] found that organic matter in a soil had a marked ameliorating influence on alkali injury, especially from sodium carbonate. High moisture was also an important factor in lowering the toxicity of soluble salts.

Guthrie and Helms,[2] using a rich garden loam, found the following concentrations slightly affecting or entirely preventing germination and growth of certain crops. (Table LXXVII.)

Of the cereals, barley and oats are the most tolerant, these being able, in some cases, to produce good crops in soil containing two-tenths per cent. of white alkali. Of the forage crops, a number of valuable grasses are able to grow on soil

[1] Harris, F. S., and Pittman, D. W., *Soil Factors Affecting the Toxicity of Alkali;* Jour. Agr. Res., Vol. XV, pp. 287-319, 1918.

[2] Guthrie, F. B., and Helms, R., *Pot Experiments to Determine the Limits of Endurance of Different Farm Crops for Certain Injurious Substances;* Agr. Gaz., N. S. Wales, Vol. 14, No. 2, pp. 114-120, 1903.

TABLE LXXVII

EFFECT OF CERTAIN CONCENTRATIONS OF SALTS ON CROPS. EXPRESSED IN PARTS PER MILLION.

CONDITION	NaCl			Na_2CO_3		
	WHEAT	BARLEY	RYE	WHEAT	BARLEY	RYE
Germination affected.	500	1000	1000	3000	2500	2500
Germination prevented	2000	2500	4000	5000	6000	5000
Growth affected.....	500	1000	1500	1000	1500	2500
Growth prevented....	2000	2000	2000	4000	4000	4000

containing considerably more than two-tenths per cent of alkali. Timothy, smooth brome, and alfalfa are the cultivated forage plants most tolerant of alkali, although they do not equal the native grasses in this respect. Cotton also tolerates a considerable amount of alkali.

Loughridge,[1] after experiments and observation for a number of years, has obtained data regarding the resistance of various crops to the several alkali salts. His results are given in part as follows, expressed in pounds to an acre to a depth of four feet. (See table LXXVIII, page 338.)

Although in general the results as to the resistance to alkali of the various crops are so conflicting, the Bureau of Soils,[2] in its alkali mapping, has been able to make a rough classification as follows. (See table LXXIX, page 338.)

178. Conditions that influence the effect of alkali.—It has already been mentioned that organic matter and a high moisture content of the soil tended to alleviate alkali toxicity. Should, however, a previously wet soil become dry, the solution, originally very dilute, would become concentrated and

[1] Loughridge, R. H., *Tolerance of Alkali by Various Cultures;* Calif. Agr. Exp. Sta., Bul. 133, 1901. See also Kearney, T. H., and Harter, L. L., *Comparative Tolerance of Various Plants for the Salts Common in Alkali Soils;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 113, 1907.

[2] Dorsey, C. W., *Alkali Soils of the United States;* U. S. Dept. Agr., Bur. Soils, Bul. 35, pp. 23-25, 1906.

TABLE LXXVIII

CROP	Na_2SO_4	Na_2CO_3	NaCl	TOTAL ALKALI
Grapes	40,800	7,550	9,640	45,760
Oranges	18,600	3,840	3,360	21,840
Pears	17,800	1,760	1,360	20,920
Apples	14,240	640	1,240	16,120
Peaches	9,600	680	1,000	11,280
Rye	9,800	960	1,720	12,480
Barley	12,020	12,170	5,100	25,520
Sugar Beet	52,640	4,000	5,440	59,840
Sorghum	61,840	9,840	9,680	81,360
Alfalfa	102,480	2,360	5,760	110,320
Saltbush	125,640	18,560	12,520	156,720

consequently toxic. High moisture should, therefore, be maintained at least as long as the crop is upon the soil.

The distribution of the alkali at different depths may have an important bearing as to its effect on plants. Young plants and shallow-rooted crops may be entirely destroyed by the concentration of alkali at the surface, while the same quantity evenly distributed through the soil, or carried by moisture to a lower depth, would have caused no injury. A loam soil, by

TABLE LXXIX

PERCENTAGE OF TOTAL SALTS IN SOIL	PERCENTAGE OF BLACK ALKALI IN SOIL	CROPS
.00— .20	.00— .05	All crops grow
.20— .40	.05— .10	All but most sensitive
.40— .60	.10— .20	Old alfalfa, sugar beet, sorghum, barley
.60—1.00	.20— .30	Only most resistant plants
1.00—3.00	above .30	No plants

reason of its greater water-holding capacity and absorptive power, will contain more alkali without injury to plants than will a sandy soil. Certain of the alkali salts exert a deflocculating action on clay soils and effect an indirect injury in that way.

In irrigated regions the injurious effects of alkali are in many cases developed only after irrigation has been practiced for a few years. This is due to what is known as a "rise of alkali" and comes about through the accumulation, near the surface of the soil, of salts that were formerly distributed throughout a depth of perhaps many feet. Before the land was irrigated the rainfall penetrated only a slight depth into the soil, and when evaporation took place salts were drawn to the surface from only a small volume of soil. When, however, irrigation water is turned on the land, the soil becomes wet to a depth of perhaps fifteen or twenty feet. During the portion of the year in which the soil is allowed to dry large quantities of salts are carried toward the surface by the upward-moving capillary water.

Although these salts are in part carried down again by the next irrigation the upward movement constantly exceeds the downward one. This is because the descending water passes largely through the non-capillary interstitial spaces, while the ascending water passes almost entirely through the capillary channels. The smaller spaces, therefore, contain a considerable quantity of soluble salts after the downward movement ceases and the upward movement begins. In other words, the volume of water carrying the salts downward in the capillary spaces is less than that carrying them upward through these spaces. Surface tension causes the salts to accumulate largely in the capillary spaces, and it is, therefore, the direction of the principal movement through these spaces that determines the point of accumulation of the alkali.

There are large areas of land in Egypt, in India, and even in France and Italy, as well as in this country, that have suf-

fered in this way, and not infrequently they have reverted to a desert state.

179. Alkali vegetation.—There are a great number of plants that seldom grow on soils other than those affected with alkali. Davy [1] states that there are 197 species restricted to alkali soils in California. Such plants are generally recognized by the farmers in the district as indicators of alkali. Care should be taken, however, in thus classifying alkali land. Such plants should occupy the land to the exclusion of less tolerant species. Some of the plants [2] whose presence should cause one to surmise alkali conditions are as follows:

Greasewood	Inkweed
Alkali-heath	Tussock-grass
Salt-grass	Bushy samphire
Salt-bush	Spike-weed
Cressa	Rabbit bush

Sage-brush, which is so often associated in popular literature with alkali, does not grow on land which carries a great amount of soluble salts. In locating land it is, therefore, a good indicator of alkali-free conditions, especially if it is growing vigorously.

180. The handling of alkali lands.[3]—Ordinarily there are two general ways in which alkali lands may be handled in order to avoid the injurious effects of soluble salts. The first of these is eradication, the second may be designated as control. In the former case an attempt is made actually to elimi-

[1] Davy, J. B., *Investigations on the Native Vegetation of Alkali Lands;* Calif. Exp. Sta. Rep., 1895-97, pp. 53-75.

[2] Harris, F. S., *Soil Alkali;* Chap. VI, New York, 1920.

[3] Dorsey, C. W., *Reclamation of Alkali Soils;* U. S. Dept. Agr., Bur. Soils, Bul. 34, 1906. Also, Hilgard, E. W., *Utilization and Reclamation of Alkali Soils;* New York, 1911. Also, Brown, C. F., and Hart, R. A., *Reclamation of Seeped and Alkali Lands;* Utah Agr. Exp. Sta., Bul. 111, 1910. Also, Dorsey, C. W., *Reclamation of Alkali Soils at Billings, Montana;* U. S. Dept. Agr., Bur. Soils, Bul. 44, 1907. Also Harris, F. S., *Soil Alkali;* Chaps. XII, XIII and XIV; New York, 1920.

nate by various means some of the alkali. In the latter, methods of soil management are employed which will keep the salts well distributed throughout the soil. In many cases soils would grow excellent crops if the alkali could only be kept well distributed through the soil layers so that no concentration that is toxic could occur, at least within the root zone. In general, steps should be taken toward the control of alkali, whether eradication is attempted or not. Under irrigation, careful attention is always wise.

181. Eradication of alkali.—Of methods designed at least partially to free the soil of alkali the commonest are: (1) leaching with under-drainage, (2) correction with gypsum, (3) scraping, and (4) flushing. Of the various methods for removing an excess of soluble salts, the use of tile drains is the most thorough and satisfactory. When this method is used in an irrigated region heavy and repeated applications of water must be made, to leach out the alkali from the soil and drain it off through the tile. When used for the amelioration of alkali spots in a semi-arid region, the natural rainfall will often in time effect the removal.

In laying tiles it is necessary to have them at such a depth that the soluble salts in the soil beneath them will not readily rise to the surface. This will depend on those properties of the soil governing the capillary movement of water. Three or four feet in depth is usually sufficient, but the capillary movement should first be estimated.

After the drains have been placed the land is flooded with water to a depth of several inches. The water is allowed to soak into the soil and to pass off through the drains, leaching out part of the alkali in the process. Before the soil has time to become very dry the flooding is repeated, and the operation is kept up until the land is brought into a satisfactory condition.

Crops that will stand flooding may be grown during this treatment, and they will serve to keep the soil from puddling,

as it is likely to do if allowed to become dry at the surface. If crops are not grown, the soil should be harrowed between floodings. The operation should not be carried to a point where the soluble salts are reduced below the needs of the crop.[1] The use of gypsum on black alkali land has sometimes been practiced for the purpose of converting the alkali carbonates into sulfates, thus ameliorating the injurious properties of the alkali without decreasing the amount. The quantity of gypsum required may be estimated from the amount and composition of the alkali. The soil must be kept moist, in order to bring about the reaction, and the gypsum should be harrowed into the surface, not plowed under. The reaction is as follows:

$$Na_2CO_3 + CaSO_4 = CaCO_3 + Na_2SO_4$$

When soil containing black alkali is to be tile-drained, it is recommended that the land should first be treated with gypsum, as the substitution of alkali sulfates or carbonates causes the soil to assume a much less compact condition and thus facilitates drainage. It also prevents the loss of organic matter dissolved by the carbonate of soda and the soluble phosphates, both of which are precipitated by the change.

Removal of the alkali incrustation that has accumulated at the surface is sometimes resorted to. Very often the rise of alkali is encouraged by applications of irrigation water, which is allowed to evaporate unretarded. The salts are thus carried upward by the capillary movement of the soil-water. This

[1] It has been suggested that elemental sulfur could be used to advantage in alkali land, especially where carbonates and bicarbonates abound. Sulfur generally oxidizes in the soil quite readily, producing an acid [see par. 221]. Instead of trying to remove all of the alkalinity by leaching, it might be more practicable to add sulfur.

Lipman, J. G., *Sulfur on Alkali Lands;* Soil Sci., Vol. II, No. 3, p. 205, 1916.

Hibbard, P. L., *Sulfur for Neutralizing Alkali Soil;* Soil Sci., Vol. XI, No. 5, pp. 385-387, 1921.

method of alkali eradication is never very efficient, and is often dangerous, as it encourages the presence of very large amounts of alkali salts in the surface soil.

Often alkali accumulations may be washed from the soil surface by turning on a rapidly moving stream of water. The texture of the soil, as well as the slope of the land, must be just right for such a procedure. Generally so much water enters the soil that the land remains heavily impregnated with alkali salts. Both this method and the previous, even if successful, are only temporary. Moreover, lands carrying so much alkali as to admit of either one of these procedures may be so heavily charged as never to yield to any form of either eradication or control.

182. Control of alkali.—Where excessive amounts of soluble salts do not exist in a soil the control of the alkali with a view of keeping it well distributed in the soil column is the best practice. The retardation of evaporation is, of course, the main object in this procedure. The intensive use of the soil-mulch is, therefore, to be advocated, especially in all irrigation operations where alkali concentrations are likely to occur. Such a method of soil management not only saves moisture, but also prevents the excessive translocation of soluble salts into the root zone. This method of control is the most economical, the cheapest, and the one to be advocated on all occasions, no matter what may have been the previous means of dealing with the alkali situation. Certain soils that are strongly impregnated with alkali may be gradually improved by cropping with sugar-beets and other crops that are tolerant of alkali and that remove large quantities of salts. This is more likely to be efficacious where irrigation is not practiced. Certain crops, moreover, while somewhat seriously injured when young, are very resistant once their root systems are developed. A good example is alfalfa, the young plants being very tender while the mature ones are extremely resistant. Temporary eradica-

tion of alkali may allow such a crop to be established. Farm manure has been found especially useful in this respect.[1] The crop once well established will then maintain itself in spite of the concentrations that may occur later.

[1] Lipman, C. B., and Gericke, W. F., *The Inhibition by Stable Manure of the Injurious Effects of Alkali Salts in Soils;* Soil Sci., Vol. VII, No. 2, pp. 105-120, 1919.

CHAPTER XVIII

SOIL ACIDITY

A CHEMICAL or physico-chemical viewpoint regarding the soil and its solution is essential in explaining many of the phenomena, especially those relating to higher plants and their nutrition. Since plants respond so markedly to their chemical environment, the importance of soil reaction has long attracted much attention. Two conditions are popularly recog nized in this respect—soil alkalinity or *alkali* and *soil acidity.* The former condition can only occur where soluble salts may concentrate in the soil and is confined largely to arid and semi-arid regions. Soil acidity, on the other hand, is common only in humid sections. So widespread is it occurrence and so marked is its influence on crop yields that its importance in a practical way surpasses that of soil alkali.

183. General nature of soil acidity.[1]—The nature of soil acidity is so little understood that it is impossible to define or explain it except in the most general terms. So-called soil acidity may be considered for practical purposes as a more or less unfavorable condition for plant growth, arising in the soil through a lack of certain active bases such as calcium and magnesium and which in practice is alleviated by the addition of some form of lime.[2]

Technically three reasons may be suggested as accounting for the harmful effects of soil acidity: (1) unfavorable hydro-

[1] MacIntire, W. H., *The Nature of Soil Acidity with Regard to its Quantitative Determination;* Jour. Amer. Soc. Agron., Vol. 13, No. 4, pp. 137-161, 1921.

[2] Lime in an agricultural sense refers to all of the compounds of calcium and magnesium commonly utilized in correcting soil acidity.

gen ion concentrations;[1] (2) presence of substances harmful to plant growth such as active aluminum, manganese and the like, the presence of which is usually accompanied by a hydrogen ion concentration beyond neutrality; and (3) improper nutrition arising from a lack of calcium as a nutrient or as a synergistic agent in facilitating the entrance of other nutrient ions into the plant.[2]

184. Hydrogen ion concentration.—A number of conditions are possible if the toxic influence of soil acidity is due to an actual acid. The harmful effect might be due to an abnormally high hydrogen ion concentration arising from (1) soluble organic or inorganic acids in the soil solution. Again it might be due to (2) insoluble acids or acid salts which, on reaction with water, produce acidity. In this case, the hydrogen ion concentration of the soil solution at any particular time would not be a measure of the so-called soil acidity.[3] A harmful hydrogen ion influence may also be ascribed (3) to soluble acids, either organic or mineral, absorbed by the soil complexes and which would become active only under certain conditions. An additional feature of the actual acidity theory may lie in (4) the selective absorption of bases by the soil, by which acidity might be developed from neutral or even alkaline salts. If the actual acidity explanation is entertained, any one or all of these phases might be considered as contributing to the deleterious effects so noticeable on certain plants.

185. Active toxic bases.—The explanation of the harmful effects of so-called soil acidity as being due to the presence of active toxic bases has of late received much attention. The

[1] Hydrogen is the one essential constituent of all acids. When dissolved in water, acids dissociate, the hydrogen ion becoming active. The strength of an acid is determined by its hydrogen ion concentration.

[2] True speaks of this coöperative relationship as *synergism.* By it calcium makes other nutrients physiologically available. True, R. H., *The Function of Calcium in the Nutrition of Seedlings;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 91-107, 1921.

[3] Rice, F. E., and Osugi, S., *The Inversion of Cane Sugar by Soils and Allied Substances and the Nature of Soil Acidity;* Soil Sci., Vol. V, No. 5, p. 347, 1918.

presence of active aluminum in so-called acid soils has been known for some time. Abbott, Conner, and Smalley [1] showed in 1913 that aluminum salts were the toxic agents in a certain unproductive soil. In 1918, Hartwell and Pember [2] proved quite definitely that, for certain soils and for certain crops, the aluminum ion was the injurious factor rather than the hydrogen ion that accompanied it. The work of Mirasol [3] indicates that active aluminum is usually present in acid soils.[4]

Although soluble iron is seldom present to an excess, its ferrous salts are known to be toxic to a greater extent than acids of the same concentration.[5] While soluble iron may accompany active aluminum, it is questionable whether it actually figures in acidity effects. The toxic influence of manganese is more probable, since it is more soluble in an acid than a neutral soil. While it is extremely toxic to plants above a certain concentration the recent work of Funchess [6] with

[1] Abbott, J. B., Conner, S. D., and Smalley, H. R., *Soil Acidity, Nitrification and the Toxicity of Soluble Salts of Aluminum;* Ind. Agr. Exp. Sta., Bul. 170, 1913.

[2] Hartwell, B. L., and Pember, F. R., *The Presence of Aluminum as a Reason for the Difference in the Effect of So-called Acid Soil on Barley and Rye;* Soil Sci., Vol. VI, No. 4, pp. 259-277, 1918.

[3] Mirasol, J. J., *Aluminum as a Factor in Soil Acidity;* Soil Sci., Vol. X, No. 3, pp. 153-193, 1920.

[4] See also, Kratzman, E., *Zur Physiologischen Wirkung der Aluminium Salz auf die Pflanze;* Chem. Ztg., Jahrgang 38, S. 1040, 1914.

Ruprecht, R. W., *Toxic Effect of Iron and Aluminum Salts on Clover Seedlings;* Mass. Agr. Exp. Sta., Bul. 161, 1915.

Miyake, K., *The Toxic Action of Soluble Aluminum Salts upon the Growth of the Rice Plant;* Jour. Biol. Chem., Vol. 25, No. 1, pp. 23-28, 1916.

Conner, S. D., *Liming in Its Relation to Injurious Inorganic Compounds in the Soil;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 113-124, 1921.

[5] Conner, S. D., *Liming in Its Relation to Injurious Inorganic Compounds in the Soil;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, p. 114, 1921.

[6] Funchess, M. J., *Acid Soils and the Toxicity of Manganese;* Soil Sci., Vol. VIII, No. 1, p. 69, 1919.

See also, Kelly, W. P., *The Influence of Manganese on the Growth of Pineapples;* Haw. Agr. Exp. Sta., Bul. 23, 1909.

Skinner, J. J., and Reid, F. R., *The Action of Manganese Under Acid and Neutral Soil Conditions;* U. S. Dept. Agr., Bul. 441, 1916.

Alabama soils indicates that it is probably of minor importance as compared with aluminum. A toxic effect from magnesium is possible, especially if there is not enough calcium to prevent it from exerting a poisonous influence. The presence of aluminum or iron in an active form is generally accompanied by a high hydrogen ion concentration due to hydrolysis,[1] which takes place readily in many soils.

186. Lack of nutrients.—Less is known regarding this condition than of the two previously discussed. The lack of sufficient nutritive calcium in an acid soil has often been suggested.[2] In addition, it may be possible that some plants require more calcium and other bases for their metabolic processes when growing on a so-called acid soil, due to the generation of particular conditions within the cells. Plants like alfalfa absorb large amounts of calcium and may find an acid soil especially unfavorable on this account.

True[3] has shown that the presence of calcium in considerable amount is necessary when certain plants are growing in nutrient solution, that other nutrient ions may penetrate the plant cells. Potassium, for example, was but slightly absorbed even when present in large amounts, unless a certain concen-

[1] Hydrolysis is a double decomposition in which one of the interacting substances is water. The water produces H^+ and OH^- ions, the former uniting with the non-metallic portion of the substance and the hydroxyl with the remainder.

Active basic radicals give, with feeble acids in water, salts which are alkaline. Active acids and active bases give neutral salts. Active acids and less active bases yield salts which are acid in reaction.

A feeble base and a feeble acid may produce a salt which is either acid or alkaline. Ammonium sulfide $(NH_4)_2S$ in solution is alkaline, since the ammonium hydroxide which tends to form is more dissociated than the hydrogen sulfide which also is present. Aluminum silicates in water hydrolize readily and since aluminum hydroxide is less dissociated than silicic acid, the hydrogen ions predominate over the hydroxyl ions and an acid reaction results.

[2] See Truog, E., *Soil Acidity: Its Relation to the Growth of Plants;* Soil Sci., Vol. V, No. 3, pp. 169-195, 1918.

Also, *Soil Acidity: Its Relation to the Acidity of the Plant Juices;* Soil Sci., Vol. VII, No. 6, pp. 469-474, 1919.

[3] True, R. H., *The Function of Calcium in the Nutrition of Seedlings;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 91-107, 1921.

tration of calcium ions was provided. This relationship, spoken of as *synergism,* may be seriously interfered with by so-called soil acidity.

187. The present status of the question.—Each of the general hypotheses which have been advanced to explain the detrimental influence of soil acidity has considerable plausible evidence in its support. Cane-sugar, which is inverted only in the presence of an acid, was found by Rice and Osugi [1] to be inverted in soils, even when the water extracts from these same soils were neutral or even alkaline. This seemed to indicate that the acidity was actual and was inherent with the soil mass rather than with the soil solution. This would also suggest the presence of insoluble or absorbed acids that might be liberated by hydrolysis, thus producing a harmful hydrogen ion concentration. Other equally valuable data are available on this phase of soil acidity. The work of Hartwell and Pember [2] and of Mirasol,[3] however, is even more conclusive in regard to aluminum as a toxic agent, especially as they studied the problem from the plant standpoint.

Conner,[4] investigating the comparative influence of sulfuric acid and aluminum sulfate on plants, has obtained some interesting data corroborating the work of Hartwell and Pember. By comparing a given hydrogen ion concentration with the same hydrogen ion concentrations plus equivalent amounts of aluminum ions, he was able to demonstrate the greater toxicity of aluminum to barley and rye in water culture. Since soluble aluminum so often accompanies an unfavorable hydrogen ion

[1] Rice, F. E., and Osugi, S., *The Inversion of Cane Sugar by Soils and Allied Substances and the Nature of Soil Acidity;* Soil Sci., Vol. V, No. 5, pp. 333-358, 1918.

[2] Hartwell, B. L., and Pember, F. R., *The Presence of Aluminum as a Reason for the Difference in the Effect of So-called Acid Soil on Barley and Rye;* Soil Sci., Vol. VI, No. 4, pp. 259-277, 1918.

[3] Mirasol, J. J., *Aluminum as a Factor in Soil Acidity;* Soil Sci., Vol. X, No. 3, pp. 153-193, 1920.

[4] Conner, S. D., *Liming in Its Relation to Injurious Inorganic Compounds in the Soil;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 113-124, 1921.

concentration, the importance of aluminum in acidity cannot be avoided.

TABLE LXXX

RELATIVE WEIGHTS OF BARLEY AND RYE GROWN IN WATER CULTURE. THE HYDROGEN ION CONCENTRATION IS EXPRESSED IN PH.[1]

TREATMENT	H ION CONCENTRATION PH	RELATIVE WEIGHTS	
		BARLEY	RYE
Check	6.3	100	100
H_2SO_4	4.2	93	95
$Al_2(SO_4)_3$	4.2	68	65
H_2SO_4	3.9	73	65
$Al_2(SO_4)_3$	3.9	47	55

The only conclusion possible at the present time is that there are probably several kinds of acidity and many degrees of the same acidity as far as toxic influences are concerned. Moreover, dissimilar plants seem to be affected differently by the same acidity, while the same plants respond diversely at different times. Hoagland[2] and others[3] have demonstrated that some plants grow better in a slightly acid medium, which

[1] The hydrogen ion concentration of an acid in solution is a measure of the dissociation of that acid and of its strength. The specific acidity of pure water is taken as 1, the number of grams of H^+ ions to a liter being .0000001 or 10^{-7}. The exponent of the power is taken as an expression of the acidity. Pure water has a PH value of 7, which is approximate neutrality. An acid solution containing 4000 times more H^+ ions would have a PH value of 3.4.

[2] Hoagland, D. R., *Relation of the Concentration and Reaction of the Nutrient Medium to the Growth and Adsorption of the Plant;* Jour. Agr. Res., Vol. XVIII, No. 2, pp. 73-117, 1919.

[3] Gillespie, L. J., *The Reaction of the Soil and Measurements of Hydrogen ion, Concentration;* Jour. Wash. Acad. Sci., Vol. 6, No. 1, pp. 7-16, 1916.

Sharp, L. T., and Hoagland, D. R., *Acidity and Adsorption in Soils as Measured by the Hydrogen Electrode;* Jour. Agr. Res., Vol. VII, No. 3, pp. 123-145, 1916.

Gillespie, L. J., and Hurst, L. A., *Hydrogen-ion Concentration—Soil Type—Common Potato Scab;* Soil Sci., Vol. VI, No. 3, pp. 219-236, 1918.

seems to indicate that the hydrogen ion concentration less than a Ph value of 7, so often reported in so-called acid soils, is concomitant with a toxic constituent or with malnutrition and is not in itself the harmful agent.[1] This argument, however, does not admit that the hydrogen ion is not in many cases the true explanation of the toxicity of certain acid soils, nor does it suggest that lack of nutrients may not be a serious consideration.

In light of the explanations offered above, it is evident that the term *soil acidity* is inadequate to express the inorganic toxicity that accompanies a hydrogen ion concentration below Ph 7, as the condition referred to is, in many cases, not due to the hydrogen ion in detrimental concentration.[2] Since the term is of long standing and since so-called acid soils almost invariably yield an acid reaction with litmus paper, the phrase will continue in use in spite of its misleading inference.

188. Why soil acidity develops.[3]—No matter what hypoth-

[1] Joffe found that while alfalfa plants experienced difficulty in becoming established in soils having high hydrogen ion concentrations due to the addition of sulfuric acid, once the seedlings became established they showed normal color and vigor and made excellent growth on soils having a Ph value as low as 3.8.

Joffe, J. S., *The Influence of Soil Reaction on the Growth of Alfalfa;* Soil Sci., Vol. X, No. 4, pp. 301-307, 1920.

[2] Researches on Danish soils extending from 1916 to 1920 show that the Ph value on different soils may vary from 3.4 to 8.0. A rather constant relationship was observed between the type of vegetation and the hydrogen ion concentration, many species being found only on soils within a certain range of Ph values. In water culture studies so-called acid-soil plants grew best at a Ph of about 4. Alkaline-soil plants seemed to give the strongest growth at a Ph of 6 to 7.

Olsen, C., *The Concentration of the Hydrogen Ions in the Soil;* Science (N. S.), Vol. LIV, No. 1405, pp. 539-541, Dec. 2, 1921.

[3] White, J. W., *Studies in Acid Soils;* Ann. Rep. Penn. State Col., 1912-1913, pp. 55-104.

Skinner, J. J., and Beattie, J. H., *Influence of Fertilizers and Soil Amendments on Soil Acidity;* Jour. Amer. Soc. Agron., Vol. 9, No. 1, pp. 25-35, 1917.

Conner, S. D., *Soil Acidity as Affected by Moisture Conditions of the Soil;* Jour. Agr. Res., Vol. XV, No. 6, pp. 321-329, 1918.

Martin, W. H., *The Relation of Sulfur to Soil Acidity and to the Control of Potato Scab;* Soil Sci., Vol. IX, No. 6, pp. 393-408, 1920.

esis may be considered as best explaining soil acidity, scientific and practical men are agreed that the addition of certain compounds of calcium and magnesium tend to alleviate the detrimental condition. Conversely, almost every one is willing to admit that the most reasonable cause of its development is the loss or inactivity of certain bases. A lack of calcium seems especially prone to allow an increased hydrogen ion concentration to develop and may at the same time encourage the activity of certain toxic bases or produce malnutrition. The tendency of all soils in a humid region is, therefore, towards acidity, their condition depending on the activity of certain factors which seem to produce such a condition. The four important factors generally specified as encouraging acidity are: (1) leaching losses, (2) cropping losses, (3) absorption phenomena within the soil, and (4) fertilizer residues.

The loss of nutrient bases from the soil has already been emphasized (par. 163) and the importance of such removal is evident from the standpoint of plant nutrition. Over a period of ten years, the removal of nutrients from the Cornell lysimeter soils,[1] by drainage and rotation cropping together, amounted to 3702, 1741, and 942 pounds to the acre, respectively, for lime (CaO), potash (K_2O), and magnesia (MgO). The loss of such amounts of bases cannot but permit the rapid development of soil acidity. No matter how well supplied the soil may be with favorable bases, it will in time become acid.

Absorption, in its influence on soil acidity, produces its effect by rendering certain bases inactive rather than by removing them from the soil. When the activity of such bases as calcium is reduced by absorptive influences, not only does the hydrogen ion concentration of the soil solution tend to increase, but the hydrolysis of compounds carrying aluminum and similar bases seems to be encouraged. The acidity as de-

[1] Unpublished data, Cornell Agr. Exp. Sta., Ithaca, N. Y.

veloped may have a nutritive relationship as well as a toxic effect.

When fertilizer salts are added to the soil, the basic ions are usually absorbed to a greater degree than the acid radicals. This tends to develop actual acidity in the soil solution, which may in itself be toxic or may facilitate the development of detrimental ions. If the crop utilizes the basic ion of the fertilizer added to a greater extent than the acid radical, it will aid in the development of acidity. If the plant, on the other hand, absorbs the acid radical, it will tend to counteract the selective absorption by the soil. The combined influences of soil and crop on ammonium sulfate tend to develop acidity, while the effect on sodium nitrate is toward alkalinity. A salt such as potassium nitrate should leave no residue.

The decomposition of organic matter, especially when green-manures are plowed under, is often considered as increasing the acidity of the soil. Such may be the case at the beginning of the decomposition process, but the data [1] available on the subject seem to indicate that organic matter, if it exerts any influence on acidity, tends to reduce rather than accentuate it. This result may occur through the liberation of bases from the organic matter as decomposition proceeds.

189. Relative tolerance of acidity by plants.—Since so many intermediate influences are possible in acid soils, and since plants respond so differently to these influences, it is impossible to forecast the relative resistance of different crops on the same soil. The response of the same crop on different acid soils is likewise difficult to foretell.

It is known that certain crops are often more tolerant to soil acidity than others. Of the common weeds sheep sorrel,

[1] White, J. W., *Soil Acidity as Influenced by Green Manures;* Jour. Agr. Res., Vol. XIII, No. 3, pp. 171-197, 1918.

Stephenson, R. E., *The Effect of Organic Matter on Soil Reaction;* Soil Sci., Vol. VI, No. 6, pp. 413-439, 1918.

Howard, L. P., *The Reaction of the Soil as Influenced by the Decomposition of Green Manures;* Soil Sci., Vol. IX, No. 1, pp. 27-38, 1920.

paint-brush, daisy, and plantain seem especially resistant. This does not mean, however, that they grow better on an extremely acid soil than on one that is slightly acid or neutral. Some of the common crops that are tolerant of acidity are strawberry, blackberry, watermelon, red-top, Rhode Island bent-grass, cowpea, soybean, rye, millet, and buckwheat. Such crops as alfalfa, red clover, timothy, maize, oats, barley, cabbage and sugar-beet seem to be susceptible in various degree to acid conditions.

Reasons for the above differences are not as yet known, since plants apparently alike in every other respect differ in their reaction to the same acid condition. The following pairs of plants may be listed as examples: watermelon and muskmelon, blackberries and raspberries, apple and quince, turnip and beet, beans and alfalfa, red-top and timothy, rye and barley. The first of each pair mentioned will grow well on acid soils, while the second crop in each case is very detrimentally affected.[1]

190. Tests for soil acidity.[2]—The great importance of soil acidity to plant growth has directed much attention towards methods for determining the acidity of the soil.

[1] Hartwell, B. L., *Need for Lime as Indicated by Relative Toxicity of Acid Soil Conditions to Different Crops;* Jour. Amer. Soc. Agron., Vol. 13, No. 3, pp. 108-112, 1921.

[2] Some of the important methods are compared and discussed in the following articles:

Schollenberger, C. J., *Relation Between the Indications of Several Lime-requirement Methods and the Soil Content of Bases;* Soil Sci., Vol. III, No. 3, pp. 279-288, 1917.

Christensen, H. R., *Experiments in Methods for Determining the Reaction of Soils;* Soil Sci., Vol. IV, No. 2, pp. 115-178, 1917.

Stephenson, R. E., *Soil Acidity Methods;* Soil Sci., Vol. VI, No. 1, pp. 33-52, 1918.

Blair, A. W., and Prince, A. L., *The Lime Requirement of Soils According to the Veitch Method, Compared with the Hydrogen-Ion Concentration of the Soil Extract;* Soil Sci., Vol. IX, No. 4, pp. 253-259, 1920.

Hartwell, B. L., Pember, F. R., and Howard, L. P., *Lime Requirement as Determined by the Plant and by the Chemist;* Soil Sci., Vol. VII, No. 4, pp. 279-282, 1919.

Such methods may be divided, for convenience of discussion, under two heads: quantitative determinations and qualitative tests. In the first case the methods devised purport to give the lime requirement of the soil. The second group of methods attempts to determine whether the soil is acid and may in addition give some general idea as to the degree of acidity.

191. Lime-requirement determinations.—A great number of methods has been advanced for the determination of the lime requirement of soils. The methods may for convenience be grouped under three heads: (1) those using a neutral salt,[1] (2) those utilizing a basic substance,[2] and (3) miscellaneous procedures.

In the first group, some neutral salt such as potassium nitrate is added to the soil and the amount of actual acidity developed is determined under suitable control. The actual acidity produced by selective absorption and basic exchange is thus taken as a measurement of the soil acidity and is generally figured to pounds of lime to the acre.

In the second group some basic substance, preferably that which is used in practice to correct acidity, is added to the soil. The amount of the basic substance necessary to render the soil alkaline or neutral is determined in pounds to the

[1] The Hopkins methods utilize potassium nitrate or sodium chloride. Calcium acetate is used in the Jones method.

Hopkins, C. G., Knox, W. H., and Pettit, J. H., *A Quantitative Method for Determining the Acidity of Soils;* U. S. Dept. Agr., Bur. Chem., Bul. 73, pp. 114-121, 1903.

Jones, C. H., *Method for Determining the Lime Requirement of Soils;* Jour. Assoc. Off. Agr. Chemists, Vol. I, No. 1, pp. 43-44, 1915.

[2] The Veitch method utilizes calcium hydroxide, the Tacke method calcium carbonate and the method proposed by Hutchinson and MacLennan calcium bicarbonate.

Veitch, F. P., *Comparison of the Methods for the Estimation of Soil Acidity;* Jour. Amer. Chem. Soc., Vol. 26, pp. 637-662, 1904.

Tacke, Br., *Über die Bestimmung der freien Humussäuren;* Chem. Ztg., Bd. 21, Heft. 20, S. 174-175, 1897.

Hutchinson, H. B., and MacLennan, K., *The Determination of the Lime Requirement of the Soil;* Chem. News, Vol. 110, p. 61, 1914.

acre. Calcium hydroxide and calcium carbonate are often used.

Many investigators consider that the hydrogen ion concentration of the soil solution is a fair measure of the lime requirement of a soil.[1] They thus assume that the concentration of the hydrogen ion is a comparative indication of the amount of lime necessary to alleviate the detrimental influences due to acidity. Bouyoucos [2] claims that the depression of the freezing point (see par. 145) may be used to measure soil acidity. He found that the depression of the freezing point was less for a neutral soil than for one either acid or alkaline.

192. The Veitch method.—In order to show something of the procedure necessary in determining the lime requirement of the soil, the Veitch method, which utilizes calcium hydroxide, will be briefly described. Eleven and and one-fifth grams of soil are placed in a suitable Erlenmeyer flask and treated with a standard lime-water solution. The amount of soil taken and the strength of the calcium hydroxide solution are such that each cubic centimeter of the latter absorbed by the soil indicates the need of 300 pounds of calcium oxide to the acre. A number of samples are run at the same time, receiving progressively larger amounts of lime-water. The

[1] Gainey, P. L., *Soil Reaction and Growth of Azotobacter;* Jour. Agr. Res., Vol. XIV, No. 7, pp. 265-271, 1918.

Gillespie, L. J., and Hurst, L. A., *Hydrogen Ion Concentration—Soil Type—Common Potato Scab;* Soil Sci., Vol. VI, No. 3, pp. 219-236, 1918.

Plummer, J. K., *Studies in Soil Reaction as Indicated by the Hydrogen Electrode;* Jour. Agr. Res., Vol. XII, No. 1, pp. 19-31, 1918.

Joffe, J. H., *Hydrogen Ion Concentration Measurements in Soils in Connection with Their Lime Requirements;* Soil Sci., Vol. IX, No. 4, pp. 261-266, 1920.

Blair, A. W., and Prince, A. L., *The Lime Requirement of Soils According to the Veitch Method Compared with the Hydrogen Ion Concentration of the Soil Extract;* Soil Sci., Vol. IX, No. 4, pp. 253-259, 1920.

[2] Bouyoucos, G. J., *The Freezing Point Method as a New Means of Determining the Nature of Acidity and Lime Requirements of Soils;* Mich. Agr. Exp. Sta., Tech. Bul. 27, 1916.

samples are brought to dryness over a steam bath and then taken up with about 100 cubic centimeters of water. The samples, after shaking, are allowed to settle, and the supernatant liquid is treated with phenolphthalein. By the use of a number of samples with varying amounts of lime-water, the amount of the reagent necessary to neutralize the soil can be approximately determined.

The objections that can be urged against the Veitch method may serve to indicate the difficulties that are in general encountered in using most of the methods for determining the lime requirement of soils. The method is, in the first place, very artificial, there being no assurance that the amount of calcium absorbed is the same as that necessary to neutralize the soil under field conditions. In the second place, it is subject to considerable error. Even with the most careful manipulation, the method is hardly accurate within 300 pounds of calcium oxide to the acre.

If the results from such a method are to be applied directly to practical liming it must be assumed that the amount of lime necessary to neutralize an acid soil is the same as that capable of alleviating the acidity for a particular crop. In light of the variable influences of acidity on plants, this is an unscientific assumption to say the least. Acidity itself is too intangible a condition. Moreover, it is in many cases not only inadvisable but also unprofitable to satisfy the full lime requirement of a soil. Some crops are unharmed or may even be benefited by moderate acidity. The selection of a lawn grass, for example, which is tolerant to acidity may allow the suppression of certain troublesome weeds that would spring up if the soil was limed.

Since the results from lime-requirement methods must be so radically modified to suit field conditions, they seem but little better in a practical way than qualitative tests, which distinguish only in a general manner between different degrees of acidity. The rapidity and simplicity of qualitative

tests give them an advantage over the somewhat questionable lime-requirement determinations. As the amount of lime applied is at best only an estimate, a simple test, rationally correlated with the many other factors that must be considered, may prove as satisfactory as a more complicated procedure.

193. Qualitative tests for acidity—litmus paper.—Perhaps the oldest test for acidity is the use of litmus paper.[1] This may be used alone or in connection with some sensitizing agent. Potassium nitrate, a neutral salt, is often utilized in this capacity. As has already been explained (par. 141), the addition of such a salt, especially to a soil lacking in active bases, results in a marked selective absorption and the development of a hydrogen ion concentration. In using litmus paper and potassium nitrate it is assumed that the selective absorption and basic exchange is an approximate measure of the so-called soil acidity.

The procedure is as follows: A small amount of the soil to be tested is placed in a small dish or other container and moistened with a neutral potassium nitrate solution. A thick batter is produced by mixing. The soil is then smoothed down and one end of a strip of neutral litmus paper is carefully applied. The reddening of the paper is an indication of acidity, while the rate of the reaction is a rough measure of the degree. The portion of the paper not in contact with the soil may be used for comparison when the change is slight. The unused end may even be moistened with distilled water to make the comparison more accurate.

194. The zinc-sulfide test.—Another qualitative test based on the same general principles has more recently been

[1] Barlow, J. T., *Soil Acidity and the Litmus Paper Method for Its Detection;* Jour. Amer. Soc. Agron., Vol. 8, No. 1, pp. 23-30, 1916.
Karraker, P. E., *The Value of Blue Litmus Paper from Different Sources as a Test for Soil Acidity;* Jour. Amer. Soc. Agron., Vol. 10, No. 4, pp. 180-182, 1918.

developed. This is the zinc-sulfide method.[1] The soil sample, usually 10 grams, is placed in an Erlenmeyer flask and treated with an excess of neutral calcium chloride and zinc sulfide. About 75 cubic centimeters of water are added. The mixture is boiled for one minute to control frothing and to develop uniform ebullition. A strip of moistened lead acetate paper is now laid over the mouth of the flask and allowed to remain there exactly three minutes, the boiling being continued at a uniform rate. The reactions involved in the test are as follows:

$$\text{Soil} + x\text{CaCl}_2 \text{ (neutral)} \leftrightarrows \text{Ca}_x \text{ Soil} + x\text{HCl}$$

$$2\text{HCl} + \text{ZnS} = \text{ZnCl}_2 + \text{H}_2\text{S}$$

$$\text{H}_2\text{S} \text{ (Expelled by boiling)} + \text{Pb}(\text{C}_2\text{H}_3\text{O}_2)_2 = \text{PbS} \text{ (black)} + 2\text{C}_2\text{H}_4\text{O}_2$$

The selective absorption and basic exchange of the soil develops actual acidity, which produces hydrogen sulfide from the zinc sulfide. The gas is driven off against the lead acetate paper, producing a black color. The principle involved is the same as that already explained for the litmus test, a different means being employed for measuring the actual acidity developed.

195. Comparison and criticism of qualitative tests.—A comparison and criticism of these two methods will amply show the advantages and disadvantages of qualitative tests[2]

[1] Truog, E., *New Method for the Determination of Soil Acidity;* Science, N. S., Vol. 40, pp. 246-248, 1914.

Truog, E., *Testing Soils for Acidity;* Wis. Agr. Exp. Sta., Bul. 312, 1920.

[2] There are a number of other qualitative tests for acidity, of which the following may be mentioned:

Ammonia test.—In this test the soil is placed in a bottle and treated with a strong solution of ammonia. After shaking, the soil is allowed to settle, the depth of the color developing in the supernatant liquid being considered as indicating the degree of acidity. This color depends on the amount and character of the soil organic matter rather than on the acidity.

Acid test for carbonates.—In this test a sample of the soil is treated with a few drops of dilute hydrochloric acid. Effervescence indicates the

in general. The litmus paper test is simple and rapid. It can be used with equal facility in the laboratory and field. While its readings may not correlate very definitely with the actual amount of lime that should be applied, it gives a basis for an estimate that in practice should include a number of factors besides so-called soil acidity. One objection to the method lies in the difficulty of obtaining sensitive litmus paper. Again the intensity of the color change is not great and in the hands of an inexperienced person may seem insignificant. In spite of its limitations, it is one of the best practical qualitative tests for soil acidity now available.

The zinc-sulfide test is much more striking than the litmus test and thus is more easily interpreted. On account of the marked change of color there is always a temptation to read into this test a quantitative value which it does not possess to any greater degree than does the litmus paper method.

The zinc sulfide test is not as rapid as the litmus test, nor is it a satisfactory field method. Moreover, it is more complex and requires a much more extensive technique. Again it does not distinguish between a neutral and an alkaline soil. Litmus paper, on the other hand, indicates alkalinity and acidity with equal facility. The zinc-sulfide test is not a method suited for those inexperienced in laboratory procedure. The deductions from the two tests, however, should be approximately the same.

196. Resume.—Soil acidity is a more or less unfavorable biological condition, which develops in soils due to the lack or

presence of sufficient favorable bases in the carbonate or bicarbonate forms. A soil, however, may be alkaline and yet fail to effervesce.

Potassium sulfo-cyanate test.—A new test has recently been proposed in which a sample of soil held in a test-tube is treated with an alcoholic solution of potassium sulfo-cyanate (KSCN). If the supernatant liquid turns red, soluble iron is present, the degree of color indicating the amount. It is assumed that the soluble iron is a comparative measure of the active aluminum in the soil and that aluminum is the toxic constituent.

Comber, N. M., *A Qualitative Test for Sour Soils;* Jour. Agr. Sci., Vol. 10, part 4, pp. 420-424, 1920.

inactivity of certain bases, especially those which tend towards soil alkalinity. These necessary bases may be rendered inactive by absorption phenomena or may be actually lost through leaching and cropping. The specific and usually deleterious influence of so-called soil acidity may be due to an excessive hydrogen ion concentration or to toxic bases such as aluminum, iron, and manganese, which become active when ionic calcium and similar bases are lacking, thus encouraging a hydrogen ion accumulation. It is not improbable that in some cases the detrimental influence may be improper nutrition, either due to a lack of calcium as a nutrient or as a synergistic agent necessary for the absorption of other nutrients by plants. These detrimental conditions are alleviated in practice by the application of some form of lime.

A number of different methods has been devised to ascertain quantitatively the lime requirements of soils. They are all more or less inaccurate. Moreover, the lime requirement of a soil and the lime necessary for best plant growth on that soil are not of necessity the same. Plants respond very differently to the diverse conditions that may develop in the various acid soils and it is seldom necessary or practicable entirely to neutralize a very acid soil in order to correct its deleterious condition. While lime-requirement methods are valuable in research, qualitative tests are sufficient in practice. The amount of lime that should be applied is determined not only by the degree and nature of the acidity but also by the character of the crops, the length of rotation, the system of fertilization, and similar factors. At best the amount of lime that should be applied to the acre is but an estimate based on many conditions, of which acidity is one. A qualitative test seems as satisfactory a basis for such an estimate as a more carefully controlled quantitative determination.

CHAPTER XIX

LIMING THE SOIL[1]

While soil acidity is a condition but imperfectly understood, most investigators are agreed that it is due to a lack or inactivity of certain bases, especially those that tend to reduce the hydrogen ion concentration of the soil solution and to give the soil an alkaline reaction. The correction of acidity obviously lies in the addition of compounds which carry the necessary bases in such forms that the acidity may be partially or wholly alleviated.

The base most commonly used to correct acidity is calcium, although magnesium is often applied, especially in connec-

[1] The following publications may be of interest:

Hopkins, C. G., *Ground Limestone for Acid Soils;* Ill. Agr. Exp. Sta., Circ. 110, 1907.

Ellett, W. B., *Lime for Virginia Farms;* Va. Agr. Exp. Sta., Bul. 187, 1910.

Brown, P. E., *Bacteriological Studies of Field Soils: The Effects of Lime;* Ia. Agr. Exp. Sta., Res. Bul. 5, 1912.

Whitson, A. R., and Weir, W. W., *Soil Acidity and Liming;* Wis. Agr. Exp. Sta., Bul. 230, 1913.

Frear, W., *Sour Soils and Liming;* Penn. Dept. Agr., Bul. 261, 1915.

Miller, M. F., and Krusekopf, H. H., *Agricultural Lime;* Mo. Agr. Exp. Sta., Bul. 146, 1917.

Mooers, C. A., *Ground Limestone and Prosperity;* Tenn. Agr. Exp. Sta., Bul. 119, 1917.

Shorey, E. C., *The Principles of the Liming of Soils;* U. S. Dept. Agr., Farmers' Bul. 921, 1918.

McCool, M. M., and Millar, C. E., *Some General Information on Lime and Its Uses and Functions in Soils;* Mich. Agr. Exp. Sta., Special Bul. 91, 1918.

Agee, Alva., *The Right Use of Lime in Soil Improvement;* New York, 1919.

Hudelson, R. R., *Keeping Soils Productive;* Mo. Agr. Exp. Sta., Circ. 102, 1921.

tion with calcium. Calcium is employed because it is not only effective with all types of acidity but because it is comparatively cheap and plentiful. Potassium in active form is too expensive, sodium is likely to generate harmful compounds in the soil, while magnesium in large amounts is sometimes harmful. Calcium compounds may be applied in excess and yet no harmful effects on plant growth are ordinarily likely to result.[1]

197. Forms of lime.—The term lime correctly used refers only to calcium oxide (CaO). In a popular and agricultural sense the scope of the word has been broadened to include all of the commercial compounds of calcium and magnesium commonly applied to the soil to correct the so-called acidity. The term in its agricultural sense refers to the following compounds either alone or in mixture: calcium oxide (CaO), magnesium oxide (MgO), calcium hydroxide ($Ca(OH)_2$), magnesium hydroxide ($Mg(OH)_2$), calcium carbonate ($CaCO_3$), and magnesium carbonate ($MgCO_3$). Such compounds as gypsum ($CaSO_4.2H_2O$), mono-calcium phosphate ($CaH_4(PO_4)_2$), and calcium silicate (Ca_2SiO_4), insofar as they are carriers of calcium, also might be spoken of as lime.

As might be expected, liming materials do not appear on the market as single compounds of magnesium or calcium, nor are they by any means pure. The better grades of the oxides and hydroxides are generally used in the trades, the more impure materials having an outlet as agricultural lime. The carbonated forms of lime have a number of different sources and vary to a marked degree in purity. Lime, in whatever form it may appear on the market, almost always carries magnesium as well as calcium, the latter usually predominating.

Three general groups of lime, as it is commercially handled,

[1] Floyd, B. F., *Some Cases of Injury to Citrus Trees Apparently Induced by Ground Limestone;* Fla. Agr. Exp. Sta., Bul. 137, 1917.
Wyatt, F. A., *Influence of Calcium and Magnesium Compounds on Plant Growth;* Jour. Agr. Res., Vol. VI, No. 16, pp. 589-619, 1916.

may be recognized: (1) burned lime,[1] (2) water-slaked or simply slaked lime,[2] and (3) carbonated lime.[3]

The devices for producing burned lime are various, ranging from the farmer's lime heap to the immense cylindrical kilns of commerce. In any case the general result is the same. The limestone with which the kiln is charged is decomposed by the heat, carbon dioxide and other gases are discharged, and calcium and magnesium oxides are left behind.[4] The purity of burned lime, as it is sold for agricultural purposes, is quite variable, ranging from 60 to 98 per cent. of calcium and magnesium oxides. As high as 40 per cent. of burned lime may be magnesium oxide, if the original stone was dolomitic. The impurities of burned lime consist of the original impurities of the limestone, such as chert, clay, iron compounds, and the like, as well as unburned fragments of the stone. These materials are often partially screened out before the product appears on the market.

Slaked lime is produced by adding water to the burned product, a hydroxide resulting from the direct union of the oxides of calcium and magnesium with water.[5] Often some of the calcium and magnesium oxides remain unslaked. Four lime compounds may, therefore, appear in freshly slaked lime, besides the original impurities of the burned materials. Com-

[1] Often spoken of as burnt lime, oxide of lime and quick lime. It may be purchased either in the lump form or in a finely ground condition. It is highly caustic and reacts readily with water.

[2] Incorrectly designated in trade as hydrated lime or lime hydrate. It is strongly alkaline and quite caustic but not to the degree exhibited by calcium and magnesium oxides. Calcium hydroxide and magnesium hydroxide are soluble in cold water to the extent of about 17 parts and .09 parts in 10,000, respectively.

[3] The carbonated forms of lime are often incorrectly spoken of as lime carbonate and carbonate of lime. Calcium and magnesium carbonates are soluble in pure cold water to the extent of only about .13 and 1.06 parts in 10,000, respectively. The reaction to litmus is slightly alkaline.

[4] $CaCO_3 + \text{Heat} = CaO + CO_2$.
$MgCO_3 + \text{Heat} = MgO + CO_2$.

[5] $CaO + H_2O = Ca(OH)_2$.
$MgO + H_2O = Mg(OH)_2$.

mercial slaked lime ranges in composition from 60 to 75 per cent. of lime expressed as calcium plus magnesium oxides. Both the burned and slaked forms of lime tend to absorb carbon dioxide from the air, producing calcium and magnesium carbonate. This is called air-slaking.[1]

A number of lime compounds are sold under the head of carbonated lime. Of these pulverized or ground limestone is the most common. There is also bog lime or marl, oyster shells and artificial carbonates. The latter are by-products from certain industries. All of these are quite variable in their content of calcium and magnesium carbonates. Pulverized limestone may vary in purity from 75 to 98 per cent., 90 per cent. being a fair average. Highly magnesian stone is generally avoided, although stone carrying from 15 to 20 per cent. of magnesium carbonate is often used. The magnesium carbonate, however, usually makes up less than 5 per cent. of the lime present.

The figures [2] quoted in table LXXI (see page 366) show the average composition of liming materials offered for sale in Pennsylvania from 1916 to 1920 inclusive.

198. Determining the need for lime.—The lack of lime in the soils of humid regions is so universal that liming will generally increase crop growth. For example, 72 per cent. of the soils of Pennsylvania [3] are sour, while 75 per cent. of the cultivated lands of Indiana [4] show acidity by the ordinary tests. While it is safe to assume that the productivity of three-fourths of the soils in the eastern part of the United States would be raised by liming, it is a question in many cases whether such treatment would pay.

[1] $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$.
$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$.

[2] Kellogg, J. W., *Lime Report;* Penn. Dept. Agr., Vol. 4, No. 2, Feb. 1921.

[3] White, J. W., *Lime Requirements of Pennsylvania Soils;* Penn. Agr. Exp. Sta., Bul. 164, 1920.

[4] Wiancko, A. T., Conner, S. D., and Jones, S. C., *The Value of Lime on Indiana Soils;* Ind. Agr. Exp. Sta., Bul. 213, 1918.

TABLE LXXI

FORM OF LIME	NUMBER OF SAMPLES	CaO %	MgO %	INSOLUBLE MATTER
Burned lime (low mg.)	59	70.01	2.97	6.19
Burned lime (high mg.)	4	52.23	33.07	2.81
Slaked lime (low mg.)	242	64.26	3.73	3.17
Slaked lime (high mg.)	107	48.87	28.07	1.58
Pulverized limestone	161	47.83	3.19	6.82
Pulverized oyster shell	4	47.60	.85	8.78
Artificial carbonate	72	50.70	2.52	1.29
Marl	22	46.75	1.00	5.90

The first point to be determined in deciding whether or not lime should be applied is in regard to the acidity and its degree. The litmus or zinc sulfide test will supply this information, although a quantitative determination may be made.[1] The general degree of acidity, unless it is very high, is not sufficient, however, in deciding whether it would be wise to lime the soil. The nature of the crops is a factor, as well as the type of the rotation, the fertilizer to be used, and to what extent farm manure and green-crops are utilized. Often special considerations are involved, such as scab on potatoes, which is encouraged by liming. All of the factors mentioned, as well as the experiences of the community with lime, should be considered in deciding whether liming would pay. If the increased crops that will probably result from an application of lime will not pay a good interest on the investment, then liming is not to be advised. An application sufficient to make possible the production of good crops of clover or alfalfa is probably all that can be used profitably.

[1] The tests are discussed in Chapter XVIII.

199. Form of lime to apply.—The experimental data regarding the relative effectiveness of the different forms of lime are not only meagre but also somewhat contradictory. In practice it is best to assume that the effectiveness of the lime depends on the amount of magnesium and calcium carried and is influenced to a much less degree by the particular combinations in which these bases may occur. For example, one and a half tons of medium to finely ground limestone carrying 50 per cent. of calcium oxide should be as effective as one ton of burned lime analyzing 75 per cent. calcium oxide. While there is a difference in the rapidity with which the various forms react, there seems to be but little difference between them over the period of a rotation when they are applied in chemical equivalent amounts.

Accepting this relationship as a practical working basis, four factors must be considered in deciding what form of agricultural lime to apply. These factors are as follows: (1) chemical equivalents, determined by chemical combination and purity; (2) cost a ton, freight on board; (3) freight; and (4) cost of haul and application to the land.

It is evident that, if the various forms of lime are equally effective in chemical equivalent quantities, once these amounts are determined the question becomes a problem in arithmetic.[1] The importance of the factors above listed can best be shown by working out an actual case.[2]

[1] $CaO \times 1.32 = Ca(OH)_2$	$MgO \times 1.44 = Mg(OH)_2$
$CaO \times 1.78 = CaCO_3$	$MgO \times 2.09 = MgCO_3$
$Ca(OH)_2 \times .76 = CaO$	$Mg(OH)_2 \times .69 = MgO$
$Ca(OH)_2 \times 1.35 = CaCO_3$	$Mg(OH)_2 \times 1.44 = MgCO_3$
$CaCO_3 \times .56 = CaO$	$MgCO_3 \times .48 = MgO$
$CaCO_3 \times .74 = Ca(OH)_2$	$MgCO_3 \times .69 = Mg(OH)_2$
$CaO \times .72 = MgO$	$MgO \times 1.39 = CaO$

[2] Calcium oxide and calcium hydroxide have an advantage over ground limestone in percentages of calcium carried and possibly in initial activity. They are, however, more disagreeable to handle and do not mix with the soil so well since they tend to lump on becoming moist. Partially or wholly carbonated lumps are often found in the soil years after the caustic lime has been applied.

Suppose that slaked lime carrying 70 per cent. of calcium oxide (CaO) sells in carload lots at $8.00 a ton and that pulverized limestone of a fair degree of fineness costs in bulk $4.50 and analyzes 50 per cent. of calcium oxide. Assume the freight as $3.00 a ton and the cost of hauling to the farm and applying to the land as $1.00 more.

The application of 1 ton of the agricultural slaked lime would cost $8.00 + $3.00 + $1.00 = $12.00. It would be necessary to apply 1.4 tons of the limestone to every ton of slaked lime. This would amount to $6.30 + $4.20 + $1.40 = $11.90. The difference in this case is very slight between the two forms. Lessening the freight or shortening the haul would give the advantage to the limestone, while increasing these would favor the use of slaked lime.

It is obvious from such calculations that a flat recommendation cannot be made in a county or community regarding the lime to use. Each individual case should be calculated, considering the cost items already mentioned.

200. Amount of lime to apply.—The possibility of an application of lime paying and the form to purchase can usually be determined with considerable assurance. Such is not the case, unfortunately, regarding the amount of a given kind of lime to apply to the acre. So many factors, of which soil reaction is only one, are active in determining crop growth that acre applications are at best estimates and often admittedly guesses. Not only the degree of acidity but the texture and the structure of the soil, the crops grown in rotation, the length of the rotation, the fertilizers used, the amount of farm manure added in a given period, and similar conditions must be considered. In ordinary practice, it is seldom economical to apply much more than a ton of limestone or its equivalent to the acre, unless the soil is very acid and the promise for increased crop yield exceptionally good. In many cases, it seems unnecessary entirely to correct the acidity of a soil in order to promote normal crop growth. The following figures,

while merely tentative, serve in a general way as guides in practical liming operations for a four- or five-year rotation with average soils. The general degree of acidity may be estimated from a qualitative test.

TABLE LXXXII

SUGGESTED AMOUNTS OF AVERAGE PULVERIZED LIMESTONE THAT SHOULD BE APPLIED TO THE ACRE UNDER VARIOUS CONDITIONS.[1]

Acidity	Limestone—Pounds to the Acre	
	Sandy Loam	Clay Loam
Moderate	1200–1500	1800–2500
Strong	1800–2500	2500–3000

201. Changes of lime in the soil.—When calcium oxide or calcium hydroxide are added to the soil, they undergo a very rapid transformation, especially if the soil is moist. The oxide takes up water and becomes the hydroxide, while the latter almost as quickly changes to the carbonate. The reactions are as follows:

$$CaO + H_2O = Ca(OH)_2$$
$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

It is generally supposed that when once the carbonate is formed in the soil or added as pulverized limestone, it is more

[1] The equivalent amounts of burned or slaked lime may readily be calculated from the chemical equivalents already quoted. Calculate for example the amount of slaked lime, carrying 65 per cent. of CaO and 5 per cent. of MgO, necessary to equal an application of 2000 pounds of adequately pulverized limestone containing 48 per cent. of CaO and 2 per cent. of MgO. The 5 per cent. of MgO in the slaked lime and the 2 per cent. of MgO in the limestone are equivalent in neutralizing capacity to 6.9 and 2.8 per cent. of CaO, respectively. The slaked lime and the limestone, therefore, carry the equivalent of 71.9 and 50.8 per cent. of CaO, respectively. $\frac{2000 \times .508}{.719} = 1413$ pounds, the amount of slaked lime necessary to equal 2000 pounds of the limestone.

or less stable, except for slow solubility. In most cases, however, the carbonate, especially magnesium carbonate, is rapidly decomposed and carbon dioxide is given off, the bases presumably entering the unsaturated aluminum silicates which are likely to be present in acid soils.[1]

The actual loss of lime in drainage water occurs through the influence of carbon dioxide which changes the insoluble carbonate to the soluble bicarbonate. The bicarbonate is washed out as such or ionizes, the calcium and the magnesium being lost in the ionic state. The presence of nitrates in the soil, either from biological activity or from fertilizers, also greatly facilitates the loss of lime from the soil in drainage. Such influence is to be especially expected during the summer and fall. In spite of the direct effect of carbon dioxide and nitrates on the loss of lime, the controlling factor seems to be the amount of water passing through the soil rather than its concentration. The following unpublished data from the Cornell University lysimeters show the losses of lime that may be expected under different conditions.[2] These figures are averages of ten years' work with Dunkirk silty clay loam.

TABLE LXXXIII

AVERAGE ANNUAL LOSS OF NITROGEN AND LIME BY LEACHING. CORNELL LYSIMETERS. AVERAGE OF 10 YEARS.

CONDITION	POUNDS TO THE ACRE PER YEAR		
	NITROGEN	LIME EXPRESSED AS CaO	LIME EXPRESSED AS $CaCO_3$
Bare soil	69.0	557.0	993.6
Rotation	7.3	345.9	617.1
Grass	2.5	363.8	648.9

[1] MacIntire, *et al.*, *The Non-existence of Magnesium Carbonate in Humid Soils;* Tenn. Agr. Exp. Sta., Bul. 107, 1914.

[2] Complete data on these lysimeters will be found in par. 163.

202. Effect of lime on the soil.—In heavy soils there is always a tendency for the fine particles to become too closely associated. Such a condition interferes with air and water movement. The granular structure that should prevail is somewhat encouraged by the addition of lime, especially the caustic forms. In practice, however, the amounts of lime applied are generally too small to have much importance in this respect.

Chemically, lime brings about many complex changes in the soil. Basic exchange is forced and certain mineral nutrients tend to become more available. The hydrogen ion concentration is lowered and deleterious bases, such as aluminum and manganese, are forced back into less active combinations. Oxidation processes seem also to be stimulated, thus favoring the elimination of organic toxins, which often develop when improper decay takes place. The charge that quicklime in normal amounts produces a rapid and detrimental oxidation of the soil organic matter is probably an over-statement.[1] While lime of all kinds promotes the oxidation of organic matter, calcium oxide, when added in rational amounts, is probably no more active over the term of the rotation than calcium carbonate.

Most of the favorable soil organisms and some of the unfavorable ones, such as those that produce potato-scab, are benefited by judicious liming. The bacteria that fix nitrogen from the air, either alone or in the nodules of some legumes, are especially stimulated by the application of lime. The change of ammoniacal nitrogen to the nitrate form, which is a biological phenomenon, requires active basic material. Otherwise this necessary transformation will not proceed. The decomposition of both carbohydrate compounds (fermentation) and of nitrogenous materials (putrefaction) depends on lime, that the decay products may be favorable.

[1] MacIntire, W. H., *The Carbonation of Burned Lime in Soils;* Soil Sci., Vol. VII, No. 5, pp. 325-446, May, 1919.

Of the general and specific influences of lime just mentioned the correction of acidity is the one commonly ascribed to it in the popular mind. The mere correction of the soil reaction, however, is probably no more important than a number of other direct and indirect influences of lime. It is evident that the benefits that may result from liming a soil will accrue from a combination of influences rather than from one effect alone.

203. **Crop response to liming.**—Much experimental work has been done in various parts of the world in determining the relative response of different crops to liming and the reason for certain well-known differences. As might be expected, the results, while in close agreement as to some crops, show striking disagreements as to others. This is to be expected, since the varying conditions of the experiments would have a marked influence on the response of the plants under consideration.

Of legume crops, alfalfa and red and white clovers respond most markedly to lime. The response of soybeans, garden peas and field peas, while less, is still quite noticeable. Alsike clover is more tolerant to acidity than red clover and, as the soil of a region declines in active bases, it is common to find it gradually replacing the latter. Japanese clover, cowpeas, vetch, and field beans do not seem to be greatly benefited by lime.

Of the non-legumes that are favorably influenced by lime, blue-grass, maize, timothy, oats, barley, wheat, and sorghum may be mentioned. Rye is less benefited by liming than is barley. Red-top, cotton, strawberries, and potatoes do not seem to be particularly stimulated by liming. Certain plants, such as blueberries, watermelons, and rhododendron are actually injured by the use of lime.

There are a number of reasons why plants may be benefited by lime, these reasons being numerous and complex enough to account for the differences in response among common

crops. The possible influences of lime on plants may be listed as follows: (1) direct nutritive action; (2) synergistic relationships either in the soil solution or in the cell-wall; (3) removal or neutralization of toxins of either an organic or inorganic nature; (4) effect on plant diseases; (5) liberation of mineral nutrients; and (6) encouragement of the biological preparation of nutrient materials.

In some cases the calcium may function as a direct nutrient; in others the intake of nutrients may be facilitated by the presence of calcium and magnesium; while in still other cases the elimination or alleviation of a toxic condition may be the important result. It is easy to conceive that any two or all three of these relationships might be fulfilled simultaneously by lime. The stimulating influence of lime might also make the plant a more active agent and thus encourage it to aid to a greater extent in the preparation of its own nutrients. Certain diseases may be retarded or even entirely suppressed by lime, as is the "finger-and-toe" disease of the Cruciferæ.

The liberation of mineral nutrients, such as potash and phosphoric acid, by the addition of lime, is somewhat uncertain although it evidently does occur in many cases.[1] The process is probably a more or less complicated physical or chemical change. The stimulation to plants by such an action is difficult to establish, since so many disturbing factors are active in obscuring the results. Lime is undoubtedly very important in the use of acid phosphate, the active compound of which is mono-calcium phosphate ($CaH_4(PO_4)_2$). In the presence of active calcium, the reversion compound is ($Ca_3(PO_4)_2$),[2] rather than the very insoluble iron and aluminum phosphates ($FePO_4$ and $AlPO_4$).

The formation of nitrates proceeds rather slowly in most

[1] Plummer, J. K., *The Effects of Liming on the Availability of Soil Potassium, Phosphorus and Sulfur;* Jour. Amer. Soc. Agron., Vol. 13, No. 4, pp. 162-171, 1921.

[2] $CaH_4(PO_4)_2 + 2CaH_2(CO_3)_2 = Ca_3(PO_4)_2 + 4H_2O + 4CO_2$

acid soils, since there is but little active basic material to stimulate the nitrifying organisms directly or to neutralize the nitrous acid that is formed.[1] The addition of lime is the most economical method of supplying this base. This response of the nitrifying bacteria to lime is a matter of great moment to crops that need large amounts of nitrate nitrogen and may account in some cases for the early response of certain crops to liming. The tolerance of some plants to acid soils might be accounted for on the supposition that they need but small amounts of nitrogen or are able to absorb their nitrogen in forms other than the nitrate.

204. Method and time of applying the lime.—Although lime is lost rapidly from most soils, appearing in the drainage water in large amounts, it does not seem to correct to any great extent the acidity of the soil layers through which it is carried.[2] Lime applied at the soil surface will tend to disappear, but will have little effect on the soil below. The action of lime seems to be a contact phenomenon and the more thoroughly it is mixed with the soil, the greater will be the number of active focii and the more rapid and effective will be the results of the treatment.

Lime is best applied to plowed land and worked into the soil as the seed-bed is prepared. It should be thoroughly mixed with the surface three to five inches of soil. Top-dressing of lime is seldom recommended except on permanent meadows and pastures. The time of year at which lime is applied is immaterial, the system of farming, the type of rotation, and such considerations being the deciding factors. The soil should not be too moist when the application is made, as the

[1] $2NH_3 + 3O_2 = 2HNO_2 + 2H_2O$.
$2HNO_2 + CaCO_3 = Ca(NO_2)_2 + H_2O + CO_2$.
$Ca(NO_2)_2 + O_2 = Ca(NO_3)_2$.

[2] Wilson, B. D., *The Translocation of Calcium in a Soil;* Cornell Agr. Exp. Sta., Memoir 17, 1918.
Stewart, R., and Wyatt, F. A., *Limestone Action on Acid Soils;* Ill. Agr. Exp. Sta., Bul. 212, 1919.

lime, especially the slaked and ground burned forms, tends to ball badly and thus thorough distribution is prevented.

A lime distributer should be used, especially if the amount to be applied is at all large. A manure-spreader can be utilized and even an end-gate seeder may be pressed into service. Small amounts of lime may be distributed by means of the fertilizer attachment on a grain drill. As with the application of any material, the evenness of distribution is as important as the form and amount of lime used and should by no means be neglected.

A discussion of the application of lime is never complete without some consideration being given to the place in the rotation at which the liming is best done. In a rotation of maize, oats, wheat, and two years of clover and timothy, the lime is often applied when the wheat is seeded in the fall. It can then be spread on the plowed ground and worked in as the seed-bed is prepared. Its effect is thus especially favorable on the new seeding. Thorne[1] has shown, however, in certain Ohio experiments, that maize is affected more favorably than any of the crops above mentioned and as the money value of this increase is practically as much as that from the hay, he favors applying the lime to the maize. With potatoes in the rotation, the lime should follow the potato crop, especially if scab is prevalent. In practice the place of lime in the rotation is usually determined by expediency, since the vital consideration is, after all, the application of lime regularly and in conjunction with a rational rotation of some kind.

205. The calcium and magnesium ratio.—A physiological balance seems to be necessary in a nutrient solution in contact with a normally growing plant. This balance varies with the plant and with numerous other conditions. The reason for such antagonistic action between the ions of certain elements is difficult to explain and many theories have been ad-

[1] Thorne, C. E., *The Maintenance of Fertility. Liming the Land;* Ohio Agr. Exp. Sta., Bul. 279, 1914.

vanced. Loew,[1] in 1901, worked out the optimum ratio for a number of different plants growing in water culture. He found that both calcium and magnesium alone were toxic and it was only when the ratio of these ions fell within certain limits that the toxicity disappeared. This ratio varied between 1 of CaO to 1 of MgO and 7 of CaO to 1 of MgO.

The question was immediately raised as to the advisability of using limestone or even burned and slaked lime, the magnesium content of which approached in any degree the calcium present. Recent field and laboratory tests have shown, however, that magnesium salts may be applied in ordinary amounts alone or with calcium compounds with impunity.[2] The absorptive capacity of the soil seems to take care in a very effective way of any toxicity that might result from a soil solution physiologically unbalanced.

206. The fineness of limestone.—The hardness of the stone, its purity, and its fineness are items of extreme importance to the manufacturer of pulverized lime. The softer the limestone, the easier the grinding and the finer the product with a given expenditure of power. The higher the percentage of calcium and magnesium, the greater is the effectiveness of a given quantity. The farmer, other conditions being more or less equal, is especially interested in the fineness of the product. It is a well-known fact that the finer the division of any material, the more rapid the solution. This, however,

[1] Loew, O., *The Physiological Rôle of the Mineral Nutrients of Plants;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 1, p. 53, 1901.

[2] Gile, P. L., and Ageton, C. U., *The Significance of the Lime-Magnesia Ratio in Soil Analyses;* Jour. Ind. and Eng. Chem., Vol. 5, pp. 33-35, 1913.

Thomas, W., and Frear, W., *The Lime-Magnesia Ratio in Soil Amendments;* Jour. Ind. and Eng. Chem., Vol. 7, No. 12, pp. 1042-1044, Dec. 1915.

Lipman, C. B., *A Critique of the Hypothesis of the Lime-Magnesia Ratio;* Plant World, Vol. 19, No. 4, pp. 83-105, Apr. 1916.

Wyatt, F. A., *Influence of Calcium and Magnesium Compounds on Plant Growth;* Jour. Agr. Res., Vol. VI, No. 16, pp. 589-619; 1916.

Stewart, R., and Wyatt, F. A., *Limestone Action on Acid Soils;* Ill. Agr. Exp. Sta., Bul. 212, 1919.

is not the only importance of fineness. Lime produces its influence largely through contact, and the finer the lime is ground, the more thorough is the mixing with the soil and the greater the number of operating focii.

White [1] presents the following significant data as a result of certain laboratory and greenhouse studies at State College, Pennsylvania.

TABLE LXXXIV

A COMPARISON OF VARIOUS GRADES [2] OF LIMESTONE WHEN APPLIED AT THE SAME RATES.

CONDITIONS	100 MESH AND SMALLER	60-80 MESH	20-40 MESH	8-12 MESH
Solubility in carbonated water.	100	57	45	28
Value in correcting acidity....	100	57	27	18
Formation of nitrates.....	100	94	56	12
Plant growth.....	100	69	22	5

These figures show that the finer grades of limestone are much more rapidly effective. Further data by the same au-

[1] White, J. W., *The Value of Limestone of Different Degrees of Fineness;* Penn. Agr. Exp. Sta., Bul. 149, 1917. Also, Thomas, W., and Frear, W., *The Importance of Fineness of Sub-division to the Utility of Crushed Limestone as a Soil Amendment;* Jour. Ind. and Eng. Chem., Vol. 7, No. 12, pp. 1041-1042, 1915.

Broughton, L. B., *et al, Tests of the Availability of Different Grades of Ground Limestone;* Md. Agr. Exp. Sta., Bul. 193, 1916.

Kopeloff, N., *The Influence of Fineness of Division of Pulverized Limestone on Crop Yield as Well as the Chemical and Bacteriological Factors in Soil Fertility;* Soil Sci., Vol. IV, No. 1, pp. 19-67, 1917.

Frear, W., *The Fineness of Lime and Limestone Application as Related to Crop Production;* Jour. Amer. Soc. Agron., Vol. 13, No. 4, pp. 171-174, 1921.

[2] Lime is graded by sieves carrying a certain number of meshes to the linear inch. An 80-mesh sieve has 80 openings to the linear inch or 6400 to the square inch. Screens rated as carrying the same number of meshes often do not give the same grade of material, due to a difference in the size of wire used. Material of 60 to 80 mesh refers to those sizes that will pass through a 60-mesh but will be held by an 80-mesh screen. A standardization of sieves and methods of expressing such analyses is much needed.

thor indicate that while the coarser lime is less rapid in its action, it remains in the soil longer and its influence should be effective for a greater period of years.

TABLE LXXXV

DECOMPOSITION OF LIMESTONE DURING THE THREE YEARS AFTER APPLICATION.

Mesh	Percentage of Decomposition	
	High Calcium Stone	High Magnesium Stone
100 mesh and smaller...	92.4	91.2
60 to 80 mesh.....	81.5	72.2
20 to 40 mesh.....	46.7	34.9
8 to 12 mesh.....	14.9	5.9

The conclusion is likely to be drawn that limestone should be ground as finely as possible. Such an assumption is at fault in several ways. In the first place, very fine lime is difficult to handle and unpleasant to distribute. Again, the cost of grinding increases very rapidly with the fineness, being entirely too expensive compared with the results attained. Moreover, finely ground material does not possess the lasting qualities of the coarser lime. Because of the cost of grinding the stone to a very fine condition and the rapidity with which such material disappears from the soil, a medium ground lime seems to be a more desirable commercial product. Such material has enough of the finer particles to give quick results and yet enough of the coarser fragments to make it last over the period of the rotation. A pulverized limestone, all of which will pass a 10-mesh sieve, 70 per cent. of which will pass a 50-mesh sieve and 50 per cent. of which will pass a 100-mesh sieve, should give excellent results and yet be cheap enough to make its use worth while.

The following figures show in an approximate way the

mechanical composition of limestone on sale in Pennsylvania for 1920[1]:

TABLE LXXXVI

MECHANICAL COMPOSITION OF SOME LIMESTONE OFFERED FOR SALE IN PENNSYLVANIA IN 1920.

LIMESTONE	AMOUNT PASSING SIEVE, MESH		
	10	50	100
1	100	98	92
2	100	99	88
3	100	89	73
4	100	70	58
5	100	57	50
6	100	44	34

207. Gypsum and other soil amendments.—Gypsum, in which form calcium sulfate ($CaSO_4.2H_2O$) is usually applied to soil, has been used for years and was popular long before commercial fertilizers were available to any extent. The use of gypsum was probably familiar to the Romans. It frequently goes by the name *land plaster*. It is widely distributed in nature and easily ground. Its beneficial effect has been noted, particularly with clover and alfalfa, crops which respond especially to potash. Its popularity has waned in recent years, however, since its effectiveness on soils where it has long been used has apparently decreased. This possibly has been due in part to the acid residue that ultimately must result from the use of such material and to the failure to liberate potassium—a property with which it has very generally been credited and which, when applied to some soils, it may possess. The experimental work in this respect is somewhat conflicting, possibly due to the fact that the con-

[1] Kellogg, J. W., *Lime Report;* Penn. Dept. Agr., Vol. 4, No. 2, 1921.

ditions of contact between the soil and the gypsum were abnormal. McMillar [1] found that the potash of certain Minnesota soils treated with one per cent. of gypsum was appreciably influenced three months after the application. When gypsum has proven beneficial to crop growth, the effect may have been due to the nutrient influence of the sulfur it contains or to the potash liberated from its soil combinations. The use of gypsum as a soil amendment is now seldom recommended, especially if the other forms of lime are available.

Sodium chloride has a marked effect on the productivity of some soils, especially when certain crops such as asparagus are grown. Wherein its effectiveness lies is not well understood. Increased fertility arising from the addition of sodium and chlorine, which are plant constituents, is probably not the reason of its influence, as these substances are usually available in soils far beyond any possible plant requirement. When common salt shows a beneficial influence, it is probably due to its tendency to liberate certain mineral nutrients such as potassium, calcium, and magnesium. Since it tends to leave an acid residue in the soil and since some form of lime will generally give better and more permanent results, the use of common salt is not recommended except in certain cases.

The use of di-calcium silicate (Ca_2SiO_4) in an experimental way as a liming material has recently received some attention. Cowles,[2] in 1917, presented data from which he concluded that

[1] McMillar, P. R., *Influence of Gypsum upon the Solubility of Potash in Soils;* Jour. Agr. Res., Vol. XIV, No. 1, pp. 61-66, 1918.

Morse, F. W., and Curry, B. E., *The Availability of Soil Potash in Clay and Clay Loam Soils;* N. H. Agr. Exp. Sta., Bul. 142, 1909.

Bradley, C. E., *The Reaction of Lime and Gypsum on Some Oregon Soils;* Jour. Ind. and Eng. Chem., Vol. 2, No. 12, pp. 529-530, 1910.

Briggs, L. J., and Breazeale, J. F., *Availability of Potash in Certain Orthoclase-bearing Soils as Affected by Lime or Gypsum;* Jour. Agr. Res., Vol. VIII, No. 1, pp. 21-28, 1917.

[2] Cowles, A. H., *Calcium Silicates as Fertilizers.* Metal. Chem. Eng., Vol. 17, pp. 664-665, 1917.

this compound was of greater value than either ground limestone or slaked lime as an amendment. He also concluded that silicon was an essential element in plant nutrition. Hartwell and Pember,[1] in 1920, found di-calcium silicate approximately equal to limestone insofar as the correction of acidity was concerned. Lettuce was used as an indicator. They found no indication that the silicon was of any value, but, as their experiments were with soil, this, of course, does not oppose the idea that silicon is an essential element in the growth of plants.

Hartwell and Pember concluded that the beneficial influence of phosphorus and calcium compounds added to the soil might, in many cases, be due to the precipitation of active aluminum quite as much as to the supplying of nutrients or the correction of actual acidity. Such a conception of the influence of liming materials may ultimately mean an increase in the number and nature of the compounds that may be used as soil amendments.

208. Importance of lime in soil improvement.[2]—The influence of successively liming a soil over a period of years may tend to raise or lower the fertility of the soil, according to the system of soil management that accompanies the applications of the lime. The use of lime alone will undoubtedly increase crop yield for a time. Basic exchange will be en-

[1] Hartwell, B. L., and Pember, F. R., *The Effect of Dicalcium Silicate on an Acid Soil;* Soil Sci., Vol. X, No. 1, pp. 57-60, July, 1920.

[2] A number of general references on the importance of lime were given at the beginning of the chapter. See also,

Wiancko, A. T., *et al., The Value of Lime on Indiana Soils;* Ind. Agr. Exp. Sta., Bul. 213, 1918.

Stewart, R., and Wyatt, F. A., *Limestone Action on Acid Soils*; Ill. Agr. Exp. Sta., Bul. 212, 1919.

Lipman, J. G., and Blair, A. W., *The Lime Factor in Permanent Soil Improvement;* Soil Sci., Vol. IX, No. 2, pp. 83-114, Feb. 1920.

Hartwell, B. L., and Damon, S. C., *Six Years' Experience in Improving a Light Unproductive Soil;* Jour. Amer. Soc. Agron., Vol. 13, No. 1, pp. 37-41, Jan. 1921.

couraged, soil bacteria will be stimulated, and more nutrients will become available for crop use. Such stimulation, however, will soon wane, and if nothing is returned to the land, productivity must ultimately drop back to even a lower level than before the lime was applied.

Lime is, to a great extent, a soil amendment and as it increases crop growth, the draft on the soil becomes larger. Greater effort is necessary, therefore, in order to maintain the fertility of the land when lime is used than when such applications are not made. Farm manure, crop residues and green-manures should be utilized to the fullest extent and when these are insufficient to keep up the potash and phosphoric acid of the soil, commercial fertilizing materials must be resorted to. Lime improperly used exhausts the soil, but when properly and rationally applied it becomes one of the important factors in the maintenance of a more or less continuous productivity.

It is interesting in this connection to consider certain figures from the Ohio Experiment Station.[1] Maize, oats, wheat and clover and timothy were grown in a five-year rotation on both limed and unlimed plats fertilized in various ways. The results of table LXXXVII (page 383) are averages for a period of twelve years.

It is immediately evident that the effectiveness of the lime was increased by the use of both fertilizers and farm manure. Conversely, the returns from the fertilizers and the manure were markedly influenced by the lime. The lime increased the effectiveness of the acid phosphate 20 per cent. The increases with the acid phosphate plus potassium chloride and with the complete fertilizers were 22 and 10 per cent., respectively. Lime increased the returns of farm manure only 4 per cent., indicating that manure itself may function as a

[1] Thorne, C. E., *The Maintenance of Soil Fertility. Liming the Land;* Ohio Agr. Exp. Sta., Bul. 279, 1914.

Table LXXXVII

RELATIVE ROTATION VALUES OF CROP INCREASES DUE TO LIMING AND FERTILIZING A STANDARD ROTATION OVER A TWELVE-YEAR PERIOD. OHIO EXPERIMENT STATION. THE ACID PHOSPHATE TREATMENT IS TAKEN AS 100 FOR THE LIME GAIN AND ALSO FOR THE UNLIMED FERTILIZER GAIN.

Fertilizers to the Rotation	Gain from Lime	Gain from Fertilizers	
		Unlimed	Limed
Acid phosphate	100	100	120
Acid phosphate plus potassium chloride	114	142	173
Acid phosphate, potassium chloride and sodium nitrate	119	232	255
Manure, 16 tons	113	287	300

soil amendment. These figures serve in a definite way to emphasize the correlation between liming and the other factors that must be considered in soil improvement and fertility maintenance.

CHAPTER XX

SOIL ORGANISMS,[1] *CARBON, SULFUR, AND MINERAL CYCLES*

A VAST number of organisms, both vegetable and animal, live in the upper layers of the soil and determine to a very large degree its dynamic character.[2] By far the greater portion of these organisms belong to plant life, producing those changes, both organic and inorganic, which control, in large degree, the productivity of the soil. While most of the organisms are so minute as to be seen, if visible at all, only by the aid of a microscope, a small proportion attain the size of the larger rodents. For convenience of discussion the life of the soil may be classified into *macro-organisms* and *micro-organisms.*

209. Macro-organisms—animal forms.—Of the macro-organisms in the soil, the animal types are chiefly (1) rodents, (2) worms, and (3) insects; and the plant forms (1) the large fungi and algæ, and (2) roots.

The burrowing habits of rodents—of which the ground squirrel, the mole, the gopher, and the prairie dog are familiar examples—result in the pulverization of considerable quanti-

[1] General references:
Lipman, J. G., *Bacteria in Relation to Country Life;* New York, 1908.
Conn, H. W., *Agricultural Bacteriology;* Philadelphia, 1918.
Marshall, C. E., *Microbiology;* Philadelphia, 1917.

[2] It has been estimated that every acre of soil contains at least 2000 pounds of living material exclusive of roots. If these organisms were confined to a surface foot of soil, weighing, when moist, 4,000,000 pounds to the acre foot, they would make up .05 per cent. by weight of the normal field soil.

ties of soil. While the effect is rather beneficial and is analogous to tillage, the activities of these animals are generally unfavorable to agricultural operations and such soil inhabitants have been more or less exterminated in arable land.

The common earthworm is the most conspicuous example of the benefits that may accrue from the presence of animals. Darwin, as the result of careful measurements, states that the quantity of soil passed through these creatures may under favorable conditions in a humid climate, amount to ten tons of dry earth to the acre annually. The earthworm obtains its nourishment from the organic matter of the soil, but takes into its alimentary canal the inorganic matter as well, expelling the latter in the form of casts after it has passed entirely through the body. The ejected material is to some extent disintegrated, and is in a flocculated condition. The holes left in the soil serve to increase aëration and drainage. The activities of the worms bring about a notable transportation of lower soil to the surface, which aids still more in effecting aëration. Darwin's studies led him to state that from one-tenth to two-tenths of an inch of soil is yearly brought to the surface of land in which earthworms exist in numbers normal to fertile soil.

Earthworms naturally seek a heavy compact soil, and it is in soil of this character that they are most needed because of the stirring and aëration that they accomplish. Sandy soil and that of arid regions, in which are found few or no earthworms, are not usually in need of their activities.

There is a less definite, and probably a less effective, action of a similar kind produced by insects. Ants, beetles, and the myriads of other burrowing insects and their larvæ effect a considerable movement of soil particles, with a consequent aëration of the soil. At the same time they incorporate into the soil a considerable quantity of organic matter.

210. Macro-organisms—plant forms.—The larger fungi are chiefly concerned in bringing about the first stages in the

decomposition of woody matter, which is disintegrated by the penetrating mycelia of the fungi. These break down the structure, and thus greatly facilitate the work of the decay bacteria. Action of this kind is largely confined to the forest and is not of great importance in cultivated soil. Another function of the large fungi is exercised in the intimate, and possibly symbiotic, relation of the fungal hyphæ to the roots of many forest trees, in soil where nitrification proceeds very slowly, if at all, for nitrates are apparently not abundant in forests.

Algæ, except in special cases, do not exist in the soil to any large extent. Certain Colorado soils,[1] however, seem to contain appreciable numbers of this form. While the presence of both the larger fungi and the algæ is interesting, their importance in soil fertility is probably rather slight.

The roots of plants are important in the soil both by contributing organic matter and by leaving, on their decay, openings which render the soil more permeable to air and water. The dense mass of rootlets, with their minute hairs, that is left in the soil after every harvest, furnishes a well-distributed supply of organic matter, which is not confined to the furrow slice, as is artificially incorporated manure. The action of roots on the soil is not by any means entirely physical. During the life of the plant the elimination of tissue and the presence of exudates make the rootlets rather important chemical agents.[2] The chemical and biological importance of decaying organic matter has already been adequately emphasized.[3]

211. Micro-organisms—protozoa.—The micro-organisms of the soil belong to the following groups: (1) protozoa, (2) fungi and algæ, (3) actinomyces, and (4) bacteria.

[1] Robbins, W. W., *Algæ in Some Colorado Soils;* Colo. Agr. Exp. Sta., Bul. 184, 1912.

[2] See paragraphs 156 and 157.

[3] See paragraphs 64 and 132.

While nematodes, rotifers, and similar organisms are sometimes found in soil, the protozoa are the only important microscopic animal group usually present. The importance of protozoa in soils was especially emphasized in 1909 by Russell and Hutchinson,[1] who maintained that the protozoan flora so interfered with the ammonia-producing bacteria as materially to lower the productivity of the soil. Partial sterilization seemed to alleviate this condition, possibly by killing the harmful protozoa. The findings of Russell and Hutchinson have resulted in much research as to the importance of protozoa in a normal soil.

While Waksman [2] found that the presence of protozoa was concomitant with low bacterial numbers, he does not consider all protozoa harmful to biological activities. Fellers and Allison,[3] in an examination of New Jersey soils, found protozoa in every sample, the number of species ranging from two to twenty-eight. Soils rich in organic matter or containing large amounts of water carried the greater number. Besides the 104 species of protozoa identified in New Jersey soils, ten genera of algæ and six of diatomes were isolated. Nematodes were common. The number of protozoa ranged from a very few to as high as 4500 to a gram of soil. When occurring in such numbers, these animals must be of considerable impor-

[1] Russell, E. G., and Hutchinson, H. B., *The Effect of Partial Sterilization of Soil on the Production of Plant Food;* Jour. Agri. Sci., Vol. III, pp. 111-144, 1909. Also, *The Effect of Partial Sterilization of Soil on the Production of Plant Food. II. The Limitation of Bacterial Numbers on Soils and Its Consequences;* Jour. Agr. Sci., Vol. V, part 2, pp. 152-221, 1913.

[2] Waksman, S. A., *Protozoa as Affecting Bacterial Activities in the Soil;* Soil Sci., Vol. II, No. 4, pp. 363-376, 1916. Also, Sherman, J. M., *Studies on Soil Protozoa and Their Relation to the Bacteria;* I. Jour. Bact., Vol. 1, No. 1, pp. 35-66, 1916. II. Jour. Bact., Vol. 1, No. 2, pp. 165-184, 1916.

Kopeloff, N., and Coleman, D. A., *A Review of Investigations in Soil Protozoa and Soil Sterilization;* Soil Sci., Vol. III, No. 3, pp. 197-269, 1917.

[3] Fellers, C. R., and Allison, F. E., *The Protozoan Fauna of the Soil of New Jersey;* Soil Sci., Vol. IX, No. 1, pp. 1-24, 1920.

tance in soils, although it is doubtful whether they are detrimental except under special conditions.[1]

212. Micro-organisms—fungi and algæ.—Of the higher fungi, molds are the only group that apparently attain any particular importance in soils, although yeasts have been found to occur and may in special cases exist in considerable numbers. It is only recently, however, that fungi have received much attention, although their presence has been noted many times. Such common genera as Fusarium, Mucor, Aspergillas, and Pencillium are usually present in normal soils. In general, a large amount of organic matter is conducive to the activity of such fungi. Molds occur in soils in both the active and the spore stage and probably pass their various life cycles entirely in the soil.

Waksman,[2] in a detailed study of soil fungi, found that most of the organisms were capable of producing considerable ammonia from nitrogenous organic matter. A large proportion of the fungi isolated were also able to decompose cellulose rather rapidly. Different soils seemed to have a distinct and characteristic fungal flora. Over one hundred distinct species of fungi were isolated by Waksman belonging to thirty-one genera. Some pathogenic species, such as different Fusaria and Alternaria, were found. The numbers ranged from 80,000 to a gram of soil under forest conditions to 14,000,000 to a gram in a meadow soil. The numbers were usually larger

[1] Koch, G. P., *Studies on the Activity of Soil Protozoa;* Soil Sci., Vol. II, No. 2, pp. 163-181, 1916.

[2] Waksman, S. A., *Soil Fungi and Their Activities;* Soil Sci., Vol. II, No. 2, pp. 103-155, 1916. Also,

McLean, H. C., and Wilson, G. W., *Ammonification Studies with Soil Fungi;* N. J. Agr. Exp. Sta., Bul. 270, 1914.

Kopeloff, N., *The Effect of Soil Reaction on Ammonification by Certain Soil Fungi;* Soil Sci., Vol. V, No. 1, pp. 541-574, 1916.

Coleman, D. A., *Environmental Factors Influencing the Activity of Soil Fungi;* Soil Sci., Vol. V, No. 2, pp. 1-66, 1916.

Brown, P. E., *The Importance of Mold Action in Soil;* Science, N. S., Vol. XLVI, No. 1182, pp. 171-175, 1917.

Conn, H. J., *The Microscopic Study of Bacteria and Fungi in Soil;* N. Y. State Agr. Exp. Sta., Tech. Bul. 64, 1918.

in the surface soil. While the microscopic algæ are probably present in soils, it has never been shown that they are of practical importance.

213. Actinomyces.—The actinomyces are a filamentous form of organisms, widely distributed in nature and are probably more nearly related to the bacteria than to the molds, although they produce spores and develop into branching forms of considerable complexity. Their production of aërial hyphæ is quite unlike the habits of bacteria. These thread organisms exist in the soil in both the vegetative and the resting stage and often make up quite a large proportion of the soil flora. They are extremely difficult to study, since they produce hard compact growths. It is questionable also, whether the growths produced artificially are exactly like those occurring in the soil.

Hiltner and Störmer [1] found that 20 per cent. of the soil organisms developing on gelatin plates inoculated from the soil were actinomyces. Conn [2] reports a range from 11 to 75 per cent. under similar cultural conditions. The average was 38 per cent. Conn estimates that 20 per cent. of the average flora consists of actinomyces. The organisms were generally greater in meadow soil than in cultivated land, indicating the relationship of these thread forms to cellulose decomposition. McBeth [3] found actinomyces of wide distribution in soils and he concludes that they are undoubtedly an important factor in the decomposition of the cellulose of the soil organic matter.

[1] Hiltner, L., and Störmer, K., *Studien über die Bakterienflora des Ackerbodens;* Kaiserliches Gesundheitsamt, Biol. Abt. Land-u. Forstw., Bd. 3, S. 445-545, 1903.

[2] Conn, H. J., *A Possible Function of Actinomycetes in Soil;* Jour. Bact., Vol. 1, No. 2, pp. 197-207, 1916.

[3] McBeth, I. G., *Studies on the Decomposition of Cellulose in Soils;* Soil Sci., Vol. I, No. 5, pp. 437-487, 1916. Also,

Waksman, S. A., and Curtis, R. E., *The Actinomyces of the Soil;* Soil Sci., Vol. 1, No. 2, pp. 99-134, 1916.

Waksman, S. A., *Cultural Studies of Species of Actinomyces;* Soil Sci., Vol. VIII, No. 2, pp. 71-207, 1919.

214. Bacteria.—Of the several forms of micro-organisms in the soil, bacteria are probably the most important. In fact, the abundant and continued growth of higher plants on the soil is absolutely dependent on the presence of bacteria. Through their action chemical changes are brought about which result in the solution of both organic and inorganic material necessary for the life of higher plants, and which, in part at least, would not otherwise be available.

Bacteria are single cell organisms and are probably the simplest forms of life with which we have to deal. They are generally much smaller than yeasts, multiplying by elongating and dividing into half. They are, therefore, often called fission fungi. Molds multiply by budding. The activities of both groups are similar, in that they produce their effects very largely by the production of enzymes.[1] The importance of enzymic influences must constantly be borne in mind in all biological transformations in the soil.

Bacteria are very small, the larger individuals seldom exceeding one or two microns (.001 to .002 m.m.) in diameter. In the soil there is good reason to suppose that there are many groups which are too small to be seen under the microscope. Such organisms may, therefore, function as a part of the colloidal matter of the soil. Many of the soil bacteria are equipped with extremely delicate vibrating hairs called flagella, which enable the organisms to swim through the

[1] Bacteria, as well as most fungi, bring about their important transformations largely by means of enzymes. These enzymes are catalytic agents and are generally considered as colloidal in nature. A number of transformations may be accelerated by enzymes, the exact reaction depending on the nature of the enzyme itself. The change in the soil of ammonia (NH_3) to the nitrate form (NO_3) is an example of *oxidation* and is spoken of as nitrification. The reversal of this action is designated as *reduction* and is probably not entirely enzymic. A *splitting action* is very common. The breaking up of glucose into alcohol and carbon dioxide is an example of this ($C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2$). A fourth reaction that may be hastened by enzymic influence is *hydrolysis.* Cane-sugar may thus quickly produce glucose and fructose ($C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6$).

soil-water. The shape of bacteria is varied in that they may be nearly round, rod-like, or spirals. In the soil the rod-shaped organisms seem to predominate.

As already stated, the primary method of multiplication of bacteria is by simple division, the process being very rapid under favorable conditions. The phenomena frequently takes place in thirty minutes. This almost unlimited capacity to increase in numbers is extremely important in the soil since it allows certain groups quickly to assume their normal functions under favorable conditions, even though their numbers were originally small.[1] Bacteria may thus be considered as a force of tremendous magnitude in the soil, held more or less in check by conditions, but ever ready to exert an influence of profound importance on crop growth.

In the soil bacteria probably exist as mats or clumps, called colonies, on and around the soil particles wherever food conditions are favorable. Natural and artificial forces tend to break up these colonies and, as many groups are flagellated, bacteria becomes well distributed through the soil. In general the greatest numbers are found in the surface layers of the soil, since conditions of temperature, aëration, and food are here more favorable. Many of the soil bacteria are able to produce spores, thus presenting both a resting and a vegetative stage. The production of spores is often extremely important as it allows the organisms to survive unfavorable conditions of many kinds.

The number of bacteria present in soil is quite variable as many conditions markedly affect their growth. The methods[2] of determining the numbers are extremely inaccurate,

[1] If a single bacterium and every subsequent organism produced subdivided every hour, the offspring from the original cell would be about 17,000,000 in twenty-four hours. In six days the organisms would greatly surpass the earth in volume. Under actual conditions such multiplication would never occur, due to lack of food and other limitations.

[2] The counting of soil bacteria is generally carried out somewhat as follows: A small sample of soil (usually .5 gram) is placed in a sterile Erlenmeyer flask and treated with 100 cc. of sterile water. The sample

since many organisms cannot grow in the artificial media commonly used. Moreover, it is almost impossible to break up the clump of colonies in such a way as to determine the number of individuals present. It is fairly certain, however, that the numbers of bacteria in soil are very large, possibly ranging from 500,000 to 100,000,000 to a gram of dry soil. Good soils seem, in general, to carry the greatest numbers. The bacterial flora, as well as the other soil organisms, fluctuate markedly with season, the numbers usually being greatest in the summer months.

215. Conditions affecting bacterial growth.[1]—Many con-

is then well shaken in order to produce a suspension containing the bacteria originally present in the soil. Dilutions of 1 to 20,000, 1 to 100,000 and 1 to 200,000 based on the original soil sample are made. Gelatin or agar plates are then inoculated, three from each dilution. After adequate incubation the colonies on the plates are counted, each colony supposedly representing one original organism. The numbers of bacteria that were present in the original soil are then calculated. The agar or gelatin of the plates generally receive a sterile extract from the soil together with certain added materials, organic or inorganic, in order that the growth of the bacteria may be hastened.

Such a count does not represent by any means all of the bacteria of the soil, as some groups will not develop at all, while others require special media. Slowly growing groups of organisms, that would probably appear if time were given, escape the count, since the plates are so quickly covered by more abundant growths. The suspension from the soil, used to inoculate the plates, does not contain all of the organisms as single individuals, since it is impossible completely to break down the clump formation. This tends to make the counts too low. Special media and technique are of course necessary in studying fungi, algæ and actinomyces.

[1] Rahn, Otto, *The Bacterial Activity in Soil as a Function of Grain-size and Moisture Content;* Mich. Agr. Exp. Sta., Tech. Bul. 16, 1912.

Plummer, J. K., *Some Effects of Oxygen and Carbon Dioxide on Nitrification and Ammonification in Soils;* Cornell Agr. Exp. Sta., Bul. 384, 1916.

Greaves, J. E., and Carter, E. G., *Influence of Barnyard Manure and Water Upon the Bacterial Activities of the Soil;* Jour. Agr. Res., Vol. VI, No. 23, pp. 889-926, 1916.

Brown, P. E. *The Influence of Some Common Humus-forming Materials of Narrow and of Wide Nitrogen-carbon Ratio on Bacterial Numbers;* Soil Sci., Vol. 1, No. 1, pp. 49-75, 1916.

Waksman, S. A., *Bacterial Numbers in Soils, at Different Depths and in Different Seasons of the Year;* Soil Sci., Vol. I, No. 4, pp. 363-380, 1916.

Gainey, P. L., *The Effect of Time and Depth of Cultivating a Wheat*

ditions of the soil affect the growth of bacteria. Among the most important of these are the supply of oxygen and moisture, the temperature, the presence of organic matter, and the acidity or the basicity of the soil.

All soil bacteria require for their growth a certain amount of oxygen. Some bacteria, however, can continue their activities with much less oxygen than can others. Those requiring an abundant supply of oxygen have been called *aërobic* bacteria, while those preferring little air are designated as *anaërobic* bacteria. This is an important distinction, because those bacteria that are of greatest benefit to the soil are, in the main aërobes, and those that are injurious in their action are chiefly anaërobes. However, it seems likely that an aërobic bacterium may gradually accommodate itself within certain limits to an environment containing less oxygen, and an anaërobic bacterium may accommodate itself to the presence of a larger amount of oxygen. It is quite possible that the aërobic and anaërobic organisms function in the soil at the same time, since a portion even of a well aërated soil is always highly charged with carbon dioxide. It is not improbable, also, that there exists a more or less beneficial interrelation between the two general groups.

Bacteria require moisture for their growth, optimum water for higher plants seemingly being the best moisture for the development and activity of favorable soil organisms of all kinds. With a decrease of moisture the soil becomes well aërated, while an excessive water supply tends to encourage anaërobic conditions. Moisture, when aëration and temperature are favorable, seems to be the main control of biological changes within the soil.

Soil bacteria, like other plants, continue life and growth

Seed-Bea upon Bacterial Activity in the Soil; Soil Sci., Vol. II, No. 2, pp. 193-204, 1916.

Greaves, J. E., and Carter, E. G., *Influence of Moisture on the Bacterial Activities of the Soil;* Soil Sci., Vol. X, No. 5, pp. 361-387, 1920.

under a considerable range of temperature. Freezing, while rendering bacteria dormant, does not kill them, and growth begins slightly above that point.[1] It has been shown that some nitrification occurs at temperatures as low as from 37° to 39° F. It is not, however, until the temperature is considerably higher that bacterial functions are pronounced. From 70° to 110° F. their activity is greatest, and it diminishes perceptibly below or above those points. The thermal death point of most forms of bacteria is between 110° and

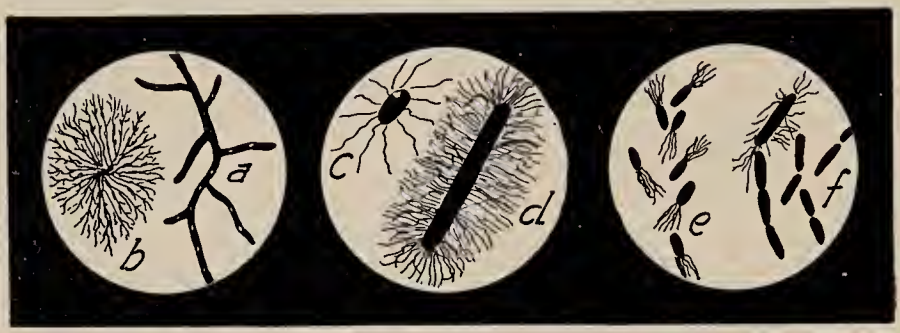


FIG. 56.—Some important decay organisms found in soils. (a), *Actinomyces* threads; (b), a colony of *Actinomyces;* (c) and (d), *Proteus vulgaris;* (e), *B. fluorescens;* (f), *B. subtilis.*

160° F., but the spore forms even resist boiling. Only in some desert soils does the natural temperature reach a point sufficiently high actually to destroy bacteria, and there only near the surface. In fact, it is very seldom that soil temperatures, other conditions being favorable, become sufficiently high to curtail bacterial activity.

The presence of a certain amount of organic matter is essential to the growth of most, but not all, forms of soil bac-

[1] In the seasonal study of bacteria it has been repeatedly noticed that the counts increased during the winter, especially after a freeze followed by a thaw. It was considered for a time that a special winter flora was present, and was able to multiply in the soil-water which failed to freeze. It is now considered that this increase is only apparent, the freezing having disrupted the bacterial clumps, thus increasing the number of colonies appearing on the plates during incubation.

teria. The organic matter of the soil, consisting as it does of the remains of a large variety of substances, furnishes a suitable food supply for a very great number of forms of organisms. The action of one set of bacteria on the cellular matter of plants embodied in the soil produces compounds suited to other forms, and so from one stage of decomposition to another this constantly changing material affords sustenance to bacterial flora, the extent and variety of which it is difficult to conceive. A soil low in organic matter usually has a lower bacterial content than one containing a large amount, and, under favorable conditions, the beneficial action, to a certain point at least, increases with the content of organic substance; but, as the products of bacterial life are generally injurious to the organisms producing them, such factors as the rate of aëration and the basicity of the soil must determine the effectiveness of the organic matter.

The so-called acidity of the soil is probably as important a factor in bacterial activity as it is to higher plants.. In general, favorable soil organisms of all kinds seem to function better in a soil carrying sufficient active base to generate conditions favorable for higher plants. An exception sometimes occurs, however, notably in the case of the "finger-and-toe" disease of certain Cruciferæ, which is retarded by liming.

The activities of many soil bacteria result in the formation of acids which are injurious to the bacteria themselves, and unless there is present some base with which these can combine, bacterial development is inhibited by such products. This is one of the reasons why lime is so often of great benefit when applied to soils, and especially to those on which alfalfa and red clover are growing. For the same reason the presence of lime hastens the decay of organic matter in certain soils, and the conversion of nitrogenous material into compounds available to the plants. As showing the value of lime in the process of nitrate formation it has been

pointed out that in the presence of an adequate supply of calcium the availability of ammonium salts is almost as high as that of nitrate salts, but where the supply of calcium is insufficient the value of ammonium salts is relatively low.

216. Organisms injurious to higher plants.—While the macro-organisms may, under certain conditions, be detrimental to the growth of higher plants, it is the smaller inhabitants of the soil that attract especial attention in this respect. While protozoa may, under special circumstances, be extremely detrimental, injurious organisms are confined mostly to fungi and bacteria. They may be entirely parasitic in their habits or only partially so, while they may injure higher plants by attacking the roots or even the tops. Those that infest parts of the plant other than the roots are not strictly soil organisms, as they pass only a part of their cycle in the soil. Some of the more common diseases produced by soil organisms are: wilt of cotton, cowpeas, watermelon, flax, tobacco, tomatoes, and other plants; damping-off of a large number of plants; root-rot; and galls.

Injurious fungi or bacteria may live for long periods in the soil, if the conditions necessary for their growth are maintained. Some of them will die within a few years if their host plants are not grown on the soil, but others are able to maintain existence on almost any organic substance. Once a soil is infected it is likely to remain so for a long time, or indeed indefinitely. Infection easily occurs. Organisms from infected fields may be carried on implements, plants, or rubbish of any kind, in soil used for inoculation of leguminous crops, or even in stable manure containing infected plants or in the feces resulting from the feeding of such plants. Flooding of land by which soil is washed from one field to another may be a means of infection.

Prevention is the best defense from diseases produced by such soil organisms. Once a disease has procured a foothold, it is often impossible to eradicate all its organisms. Rota-

tion of crops is effective for some diseases, but entire absence of the host crop is often necessary. The use of lime is beneficial in the case of certain diseases. Chemicals of various kinds have been tried with little success. Steam sterilization is a practical method of treating greenhouse soils for a number of diseases. The breeding of plants immune to the disease affecting its particular species has been successfully carried out in the case of the cowpea and cotton, and can doubtless be accomplished with others.

In regions in which farming is confined largely to one crop or to a limited number of cereals, it is the common experience that yields decrease greatly in the course of a score of years after the virgin soil is broken. The cause for this is attributed by Bolley,[1] in large measure, to a diseased condition of the plants, due to the growth of various fungi that inhabit the soil and attack the crops grown on it. He reports that he experimented with pure cultures taken from wheat grains, straw, and roots, and has demonstrated that certain strains or species of Fusarium, Helminthosporium, Alternaria, Macrosporium, Colletotrichum, and Cephalothecium are directly capable of attacking and destroying growing plants of wheat, oats, barley, brome-grass, and quack-grass, and that within limits the disease may be transferred from one type of crop to another.

217. The beneficial influences of soil organisms.—While the macro-organisms of the soil are usually beneficial to higher plants, the more important relationships are occupied by the micro-organisms. The micro-organisms of the soil take an active part in removing dead plants and animals from the surface of the land, and in bringing about the other operations that are necessary for the production of higher plants. The first step in preparation for plant growth is to remove the remains of plants and animals that would otherwise accumulate to the exclusion of higher plants. These are decomposed

[1] Bolley, H. L., *Wheat;* N. Dak. Agr. Exp. Sta., Bul. 107, 1913.

through the action of organisms of various kinds, the intermediate and final products of decomposition assisting plant production by contributing nitrogen, and certain mineral compounds that are a directly available source of plant nutrients, and also by the effect of certain of the decomposition products on the mineral substances of the soil, by which they are rendered soluble and hence available to plants.

Through these operations the supply of carbon and nitrogen required for the production of organic matter is kept in circulation. The complex organic compounds in the bodies of dead plants or animals, in which condition higher plants cannot use them, are, under the action of micro-organisms, converted by a number of stages into the simple compounds used by plants. In the course of this process, a part of the nitrogen is sometimes lost into the air by conversion into free nitrogen, but fortunately this may be recovered and even more nitrogen taken from the air by certain other organisms of the soil.

Higher fungi and actinomyces are particularly active in the early stages of decomposition of both nitrogenous and non-nitrogenous organic matter. Molds are capable of ammonifying proteins, and even re-forming complex protein bodies from the nitrogen of ammonium salts. Certain of the molds and of the algæ are apparently able to fix atmospheric nitrogen, and contribute in addition a supply of carbohydrates required for the use of the nitrogen-fixing bacteria. While the higher fungi are important in such transformations, their activities in almost every stage are excelled by those of the bacteria. Because of this, the vital biological transformations within the soil are generally ascribed to bacterial action, the bacteria receiving the greatest attention of the numberless organisms making up both the soil flora and fauna.

218. Biological cycles.—Because of a lack of knowledge regarding the flora and fauna of the soil, it is obviously im-

possible to discuss in detail the transformations caused by individual species of organisms or even by groups of related species. From the standpoint of soil fertility such an attempt is unnecessary, as a practical understanding of the changes through which a given soil constituent passes as it is prepared for plant nutrition, is much more important than the possession of specific knowledge regarding the organisms concerned. As a consequence it has become customary to discuss the biological transformations of the more important soil constituents, including as much regarding the specific organisms and groups of organisms involved as is consistent with a clear fertility viewpoint.[1] Four cycles are generally recognized, as follows: (1) the carbon cycle, (2) the sulfur cycle, (3) the mineral cycle, and (4) the nitrogen cycle.

219. The carbon cycle.—Since all organic compounds carry carbon, nitrogenous as well non-nitrogenous materials are involved in the carbon cycle. Nevertheless attention will be directed for the time being only toward the carbon and the changes that it undergoes from the time it enters the soil until it is removed either by aëration, leaching, or by plant absorption.

Most of the carbon compounds enter the soil as plant tissue, although animal remains contribute appreciable amounts. These carbonaceous materials are immediately attacked in the soil by a host of different organisms capable of producing fermentation. While such bacteria as *Bacillus subtilis, Bacillus mycoides,* and the like have a great deal to do with the decay processes, they are by no means the only agents. Most of the microscopic fungi, as well as the larger fungi and algæ,

[1] There are two general ways of studying the soil flora. A classification of the organisms may be attempted. This requires the isolation and study of individuals and has so far met with but little success. The second approach is a biochemical one, in which the transformations occurring in the soil are studied first, the specific organisms involved being a secondary consideration. The determination of the capacity of the soil to produce ammonia is an example of this method of study.

aid in the initial transformation, being particularly effective in decomposing cellulose. The actinomyces, present in such large numbers, seem to be especially fitted for the breaking down of such resistant material.

The result of these complex decomposition processes is the formation of a partially decayed group of carbon-bearing material, some being quite simple while others are extremely complicated. The change is accompanied through its entire course by the formation of carbon dioxide and water, the end-products of carbohydrate decay. The same heterogeneous group of soil organisms, which initiate the simplification of carbonaceous materials, seem to continue the process until only the end products and the more resistant portions of the original tissue remain.

The transformations above discussed are not the only sources of carbon dioxide within the soil. Some carbon dioxide is brought down in rain-water, while still more is given off by the roots of living plants (see par. 156). Moreover some carbon dioxide is obtained from the inorganic matter of the soil, especially if the land has recently received an application of limestone. The reactions within the soil seem to decompose such carbonates rather readily, carbon dioxide being given off (see par. 201).

220. The loss of carbon from the soil.—Carbon dioxide, the importance of which has already been fully discussed (par. 132), may suffer transformation in a number of ways in the soil. It may be lost (1) to the atmospheric air; (2) it may react with the mineral constituents of the soil and be held at least temporarily by the soil mass; or (3) it may be removed by leaching. Since the soil-water is always more or less charged with carbon dioxide and since it carries carbonate and bicarbonate salts, considerable carbon is continually being removed in this way. In this regard the figures from the Cornel lysimeter tanks[1] are especially interesting.

[1] Unpublished data. Cornell Agr. Exp. Sta., Ithaca, N. Y.

The data are expressed in pounds to the acre and are averages of ten years' experimentation. The carbon was lost as the bicarbonate, only traces of carbonates being present. (See table LXXXVIII, page 402).

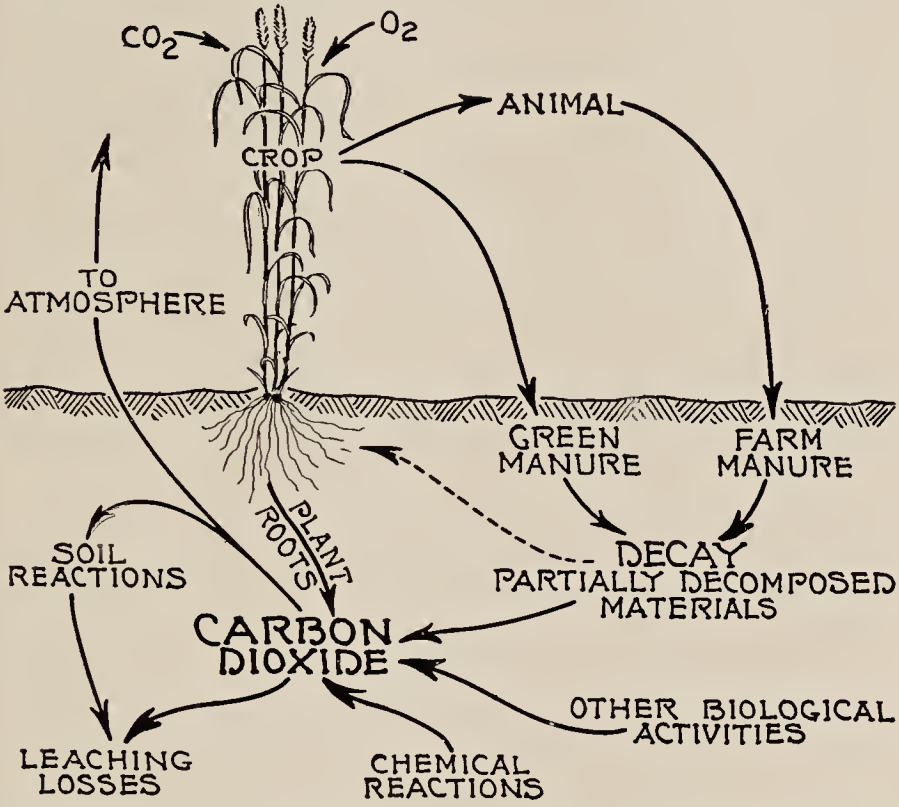


FIG. 57.—Diagram showing the transformations of carbon, commonly spoken of as the "carbon cycle."

It is apparent that a drainage loss of about 1200 pounds of bicarbonate (HCO_3) may be expected each year to the acre, without considering the carbon dioxide which is respired to the atmosphere. This latter loss probably at least equals, if it does not greatly exceed, the loss of carbon in the bicarbonate form. Together they cause a disappearance of several hundred pounds of carbon a year under the conditions main-

TABLE LXXXVIII

LOSS OF CARBON FROM THE SOIL IN DRAINAGE, EXPRESSED IN POUNDS TO THE ACRE PER YEAR. CORNELL LYSIMETERS.

TREATMENT	HCO_3 (POUNDS)	CARBON (POUNDS)
Bare soil	1391	273
Rotation	1350	265
Grass	1193	234

tained in the Cornell lysimeters. The application of two tons of green-manure to the acre would be necessary to replace even the drainage loss cited above.

Small amounts of carbon may be removed by means other than drainage or diffusion into the atmospheric air. Numerous investigators [1] have shown that plants are capable of assimilating various organic materials. Recently it has been demonstrated that higher plants may utilize a considerable variety of carbohydrate compounds.[2] Such materials, when thus assimilated, no doubt supply the plant with energy and thus are foods rather than nutrients. The ready response of certain crops, such as maize, to applications of farm manure lends plausibility to the theory that considerable carbon may be removed from the soil by plants and that the carbon dioxide of the air is not the only immediate source of the element carbon.

221. The sulfur cycle.—Sulfur is an essential plant nu-

[1] Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Centrlb. f. Bakt., II, Band 30, S. 513-547, 1911.

[2] Mazé, P., *Influence, sur le développement de la plante, des substances minérales qui s'accumulent dans ses organes comme résidus d'assimilation;* Compt. Rend. Sci., Paris, Tome 152, pp. 783-785, 1911.

Ravin, P., *Nutrition carbonée des plantes à l'aide des acides organique libres et combinés;* Ann. Sci. Nat. Bot., Ser. 9, No. 18, pp. 289-446, 1913.

Knudson, L., *Influence of Certain Carbohydrates on Green Plants;* Cornell Agr. Exp. Sta., Memoir 9, July 1916.

trient, being utilized by such crops as alfalfa, turnips, and cabbage in much larger amounts than is phosphorus. Although sulfur probably seldom becomes a limiting factor in crop production (see par. 264), where rational methods of soil management are practiced, its transformations in the soil are of great importance.

Sulfur is absorbed by the plant as the sulfate ion and consequently all forms of soil sulfur must be changed to the sulfate before the plant may benefit to any degree. This transformation of sulfur, both organic and inorganic, to the sulfate form, insofar as it is biological, has been termed by Lipman,[1] *sulfofication.* The reactions involved after hydrogen sulfide or free sulfur are formed may be written as follows:

$$2H_2S + 3O_2 = 2H_2SO_3$$
$$S + H_2O + O_2 = H_2SO_3$$
$$H_2SO_3 + CaH_2(CO_3)_2 = CaSO_3 + 2H_2O + 2CO_2$$
$$2CaSO_3 + O_2 = 2CaSO_4$$

While the oxidation reactions cited above are not entirely biological, purely chemical changes occurring to a slight degree, the decay processes preceding them are due wholly to bacteriological and allied influences. The organisms involved in sulfofication are probably many, including the higher forms of fungi as well as bacteria. The organisms that function in the carbon cycle no doubt are active in the sulfur transformations as well.

The possible sources of the sulfur which is found in the sulfur cycle are four: (1) plant and animals tissue, (2) fertilizers, (3) rain-water, and (4) the inorganic sulfur of the soil itself. The organic source is probably the most important means by which the sulfur supply of the soil is augmented in practice. The addition of farm manure and the turning under of crop residues and green-manures will do

[1] Lipman, G. J., *Suggestions Concerning the Terminology of Soil Bacteria;* Bot. Gaz., Vol. 51, pp. 454-460, 1911.

much to retard the sulfur reduction which is constantly occurring. Fertilizers, such as acid phosphate, ammonium sulfate, and potassium sulfate, may also be valuable sources of sulfur. The amount of sulfur carried down in rain-water is largely in the sulfate form and is quite variable, ranging from a few pounds of SO_3 yearly to the acre to over 160 pounds. The rainfall addition at Ithaca,[1] New York, is about 65 pounds of SO_3 to the acre a year, while Stewart[2] reports a yearly gain to the acre of 113 pounds at the University of Illinois. The inorganic sulfur of the soil also constantly tends to enter the sulfur cycle and must be reckoned with in any study of sulfofication.

222. Loss of sulfur from the soil.—The loss of sulfur from the soil under normal agricultural conditions occurs in two ways: (1) losses in drainage, and (2) removal by cropping. Unless such losses can adequately be met by additions of sulfur or sulfur compounds, it is obvious that this element will become a limiting factor in crop growth. The figures[3] from the Cornell lysimeters are very instructive in this regard. The soil used was a Dunkirk silty clay loam.

TABLE LXXXIX

AVERAGE ANNUAL LOSS OF SULFUR (as SO_3) BY PERCOLATION AND CROPPING. CORNELL LYSIMETERS. AVERAGE OF 10 YEARS.

CONDITION	POUNDS TO THE ACRE OF SO_3 LOST THROUGH		
	DRAINAGE	CROP	TOTAL
Bare soil.....	132.0	——	132.0
Rotation.....	108.5	41.0	149.5
Grass.....	111.0	29.2	140.2

[1] Wilson, B. D., *Sulfur Supplied to the Soil in Rain Water;* Jour. Amer. Soc. Agron., Vol. 13, No. 5, pp. 226-229, 1921.

[2] Stewart, R., *Sulfur in Relation to Soil Fertility;* Ill. Agr. Exp. Sta., Bul. 227, 1920.

[3] Unpublished data, Cornell Agr. Exp. Sta., Ithaca, N. Y.

Since the sulfur added to the soil at Ithaca, New York, amounts to only 65 pounds of SO_3 yearly to the acre, other sources of sulfur assume considerable importance in fertility practice. It seems probable, however, that the judicious use of fertilizers carrying sulfur in conjunction with farm manure, green-manure and crop residues, will adequately care for the sulfur needs of the average soil (see par. 264).

223. Factors influencing sulfofication.—The sulfofying activities of the soil flora are greatly influenced by conditions within the soil. Brown [1] has found that the addition of farm manure and green-manure greatly stimulates sulfofication, although carbohydrates alone seem to exert a depressing influence. Lime, unless applied in very large amounts, encouraged the transformation of the sulfur compounds, increasing the amount of sulfates present in the soil. The reason for this influence is evident from the reactions already quoted. The partial oxidation of hydrogen sulfide or of free sulfur produces sulfurous acid (H_2SO_3), which exerts a retarding influence on further action, unless a base, such as calcium or magnesium, is present to form a salt of this acid.

Brown's results also indicate the preponderant influence of aëration, moisture, and organic matter on sulfofication. Optimum conditions for crop growth, as far as these factors are concerned, seem also to be optimum for the transformation of sulfur compounds in the soil. These same conditions also favor satisfactory reactions within the carbon cycle as well.

[1] Brown, P. E., and Kellogg, E. H., *The Determination of the Sulfofying Power of Soils;* Jour. Biol. Chem., Vol. XXI, No. 1, pp. 73-89, 1915.

Brown, P. E., and Johnson, H. W., *Studies in Sulfofication;* Soil Sci., Vol. I, No. 4, pp. 339-362, 1916.

Brown determines the sulfofying power of soil by adding .1 gram of Na_2S or free sulfur to 100 grams of fresh soil, adjusting the moisture content to optimum and incubating from five to ten days. The sulfates are then determined by shaking the soil with water for seven hours, filtering and precipitating the sulfates with barium chloride. The amounts of sulfates are estimated in a sulfur photometer. An untreated sample of soil should be run as a check.

224. The sulfur compost.—It has been noted by a number of experimenters that the presence of sulfur compounds in the soil and especially elemental sulfur tends to develop considerable acidity. The cause of this acidity has already been explained. In 1916, Lipman [1] and his co-workers suggested that a practical use be made of sulfofication in rendering certain mineral nutrients, such as potash and phosphoric acid, available. Lipman devised a compost of sulfur and raw rock phosphate. His results seem to indicate that sufficient acid might be formed by biological oxidation appreciably to influence the solubility of the rock phosphate.

Brown and Warner [2] later used a compost of sulfur, farm manure and raw rock phosphate. Remarkable increases in the solubility of phosphoric acid, measured by extraction with a solution of ammonium citrate, were recorded. The results of Lipman, Brown, and Warner have been corroborated by Ames and Richmond,[3] and Shedd.[4] Ames and Boltz [5] in 1919 found that sulfur composted with feldspar appreciably influenced the solubility of potash. Such results as those recorded above indicate the importance of sulfofication in the soil under ordinary circumstances, as well as a possible value in a more intensified procedure.

The practicability of using sulfur composts on the farm

[1] Lipman, J. G., *et al., Sulfur Oxidation in the Soil and Its Effects on the Availability of Mineral Phosphates;* Soil Sci., Vol. II, No. 6, pp. 499-538, 1916.

[2] Brown, P. E., and Warner, H. W., *Production of Available Phosphorus from Rock-Phosphate by Composting with Sulfur and Manure;* Soil Sci., Vol. IV, No. 4, pp. 269-282, 1917.

[3] Ames, J. W., and Richmond, T. E., *Effect of Sulfofication and Nitrification on Rock Phosphate;* Soil Sci., Vol. VI, No. 4, pp. 351-364, 1918.

[4] Shedd, O. M., *Effect of Oxidation of Sulfur in Soils on the Solubility of Rock-Phosphate and on Nitrification;* Jour. Agr. Res., Vol. XVIII, No. 6, pp. 329-345, 1919.

[5] Ames, J. W., and Boltz, G. E., *Effect of Sulfofication and Nitrification on Potassium and Other Soil Constituents;* Soil Sci., Vol. VII, No. 3, pp. 183-195, 1919. See also, Tottingham, W. E., and Hart, E. B., *Sulfur and Sulfur Composts in Relation to Plant Nutrition;* Soil Sci., Vol. XI, No. 1, pp. 49-65, 1921.

is yet to be determined, and will depend on a number of factors. The soil must, of course, be deficient in the constituent composted with sulfur. Otherwise, an application of sulfur alone would give just as good results. Again the cost of composting must be reckoned with. It yet remains to be proven by crop growth whether the efficiency of sulfur is any greater when it is composted with such materials as raw rock phosphate and farm manure and applied to the soil, than when these materials are added separately.

225. The mineral cycle.—The strictly mineral constituents of the soil seem to undergo as complex and intricate transformations as do the elements that are considered as more closely related to the soil organic matter, such as carbon, nitrogen and sulfur. While a part of the mineral cycle is purely chemical or physico-chemical, the biological phase is by no means unimportant. In fact, were it not for the influence of organisms within the soil, little or no mineral matter, such as phosphoric acid and potash, would ever become available to higher plants.

When plant or animal tissue enters the soil, it undergoes decay in the manner already described, the ash constituents being liberated and either utilized directly by higher plants again or converted into a part of the soil mass. The main source of the mineral nutrients for any plant is of course the inorganic portion of the soil rather than the organic part. It is thus necessary to investigate what influence, if any, soil organisms have on such material.

The action of organisms on the inorganic portions of the soil is of two kinds: (1) direct, and (2) indirect. In the former the soil organisms themselves attack the mineral matter, rendering part of it available. Some of this soluble material is absorbed by the organisms, becoming a part of the cell contents. When the fungus or bacterium dies, this material through decay again becomes available and may be used by higher plants. While most soil organisms probably

function to a certain extent in this direction, some are especially active. It is known that *B. mycoides, B. mesentericus* and *B. megatherium* are capable of assimilating phosphorus in considerable quantities, while such organisms as *Beggiotoa* and *Ophidomonas* store up sulfur in large amounts. In the same way iron, potassium, calcium, and like elements may be utilized. While such biological action is at the time a direct competition with higher plants, more mineral material is ultimately available in the soil through such activities.

While the direct effects of organisms on soil minerals is no doubt very important, the indirect influences seem to be more vital in a practical way. While this indirect influence may be in part enzymic, it is probably largely due to the production of carbon dioxide, which accompanies all types of life processes. The sulfurous acid and nitrous acid of the sulfur and the nitrogen cycles, respectively, are also active to a certain extent. The preceding discussion of the sulfur compost indicates how vigorous the biological oxidation within the sulfur cycle may become under certain conditions. In the soil, however, carbon dioxide is probably by far the most important.[1] Since the significance of carbon dioxide has already been adequately discussed (pars. 17, 58 and 132), it is sufficient at this point to state that this gas, because of its large amounts and its intimate relationship to the mineral material, is probably the most effective solvent agent in the soil.

[1] Typical reactions involving tri-calcium phosphate, orthoclase and calcium carbonate are as follows:

$$Ca_3(PO_4)_2 + 2CO_2 + 2H_2O = Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2.$$

$$2KAlSi_3O_8 + CO_2 + 2H_2O = H_4Al_2Si_2O_9 + K_2CO_3 + 4SiO_2.$$

$$CaCO_3 + H_2O + CO_2 = Ca(HCO_3)_2.$$

CHAPTER XXI

SOIL ORGANISMS—THE NITROGEN CYCLE

Of the various nutrient materials applied to the soil for the use of plants nitrogen has the highest commercial value and is absorbed in very large quantities. Moreover, nitrogen is lost from the soil in considerable amounts in drainage water and possibly to some extent in gaseous form. The great importance of this element and of its compounds in agriculture and the possibility of it becoming a limiting factor in crop production has lead to much study regarding its reactions and movements in the soil.

The original source of the world's supply of combined nitrogen has been the atmosphere and, as the free gas is exceedingly inert,[1] the natural forces which facilitate its combination must be extremely powerful. The movement of nitrogen from air to soil, from soil to plant, from plant back to soil or to animal, and from animal to soil, with a return to air at various stages, involves many forces, many factors, many organisms, and many reactions. These complicated changes are spoken of as the nitrogen cycle.

226. The nitrogen cycle.—In tracing the various transformations through which the nitrogen passes, the conspicuous feature is the great complexity of the cycle. Apparently the nitrogen cycle is much more extended and intricate than either the carbon or sulfur cycles. This complexity, however,

[1] Because nitrogen is such an inert gas, it must not be inferred that it forms inactive compounds with other materials. In combination it is extremely active, seemingly being the basis of all plant and animal life processes.

is more apparent than real. The transformation of nitrogen has received so much attention and study that more is known regarding the changes involved. The other cycles are probably just as extended and complicated, the lack of knowledge forcing a simpler presentation.

From the standpoint of soil fertility the compounds that are produced in the nitrogen cycle and the relation of these materials to plant growth are of major consideration. While the organisms involved in the transformation should receive as much attention as is practicable, the approach should be by means of biological-chemistry rather than through bacteriology.

It must not be inferred that the carbon, sulfur and nitrogen cycles are distinct or that transformations may proceed in one with no activity in the others. As a matter of fact, the cycles are interlocked in a hopelessly intricate manner. The decomposition of proteid matter involves all of the cycles already mentioned. The carbon, sulfur, and nitrogen undergo distinctly different transformations, but the changes are so closely related as to make definite lines of distinction very difficult. Proteid matter may produce urea, carbon dioxide, water, and sulfates. Certain of these products often strongly influence the solubility of the soil minerals. Thus, the four cycles already mentioned would be involved in the decomposition of one original compound.

227. Decay and putrefaction.[1]—The decomposition of most nitrogenous matter is very rapid in a normal soil, the putrefactive influences producing partially decayed substances of great variety.[2] Some of these materials are very complicated, while others are capable of being absorbed di-

[1] Decomposition and decay are general terms, referring to all types of biological degradation. Fermentation refers to the decomposition of carbohydrates, while putrefaction has to do with nitrogenous materials. The two latter terms are generally very loosely used.

[2] Lathrop, E. C., *Protein Decomposition in Soils;* Soil Sci., Vol. I, No. 6, pp. 509-532, 1916.

rectly by plants without further change. Carbon dioxide and water are formed continuously as the process advances. The sulfur of the proteid compounds produces hydrogen sulfide or free sulfur and later sulfates.

Hutchinson and Miller,[1] as well as other investigators, have studied the question of the assimilation of nitrogenous organic compounds by higher plants. The general conclusions indicate that such a source of nitrogen is quite important and sometimes allows the plant to benefit markedly from the assimilation of such materials. Maize, for example, seems to be particularly stimulated by farm manure, which carries large amounts of organic nitrogenous compounds such as urea. Acetamide, urea, barbituric acid, creatinine, alloxan, peptone, and a number of other organic compounds have been shown to be available to certain higher plants.

Decay and putrefaction are carried on by a large number of organisms, the higher fungi as well as such bacteria as *B. subtilis, B. mycoides,* and similar micro-organisms engaging in the decomposition processes. Some of the characteristic, although not constant, products formed in the putrefaction of albumin and proteins are albumoses, peptones, and amino acids, followed by the formation of cadaverine, putrescine, skatol, and indol. Where an abundant supply of oxygen is present, or where a sufficient supply of carbohydrates exists, the latter substances are not formed. There are many other products of putrefaction, including a number of gases, as carbon dioxide, hydrogen sulfide, marsh gas, phosphine, hydrogen, nitrogen, and the like.

Present-day knowledge of the subject does not make it possible to present a list of the organisms concerned in each step, or to name all the intermediate products formed. For the student of the soil the first consideration is a knowledge of

[1] Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Centrlb. f. Bakt., II, Band 30, Seite 513-547, 1911.

the circumstances under which the nitrogen is made available to plants, and the conditions that are likely to encourage its loss from the soil.

228. **Ammonification** may be considered as the second step in the simplification which nitrogenous compounds undergo in the soil. As the name implies, it is the stage of the decay process in which ammonia is one of the important products. Like other processes of decomposition, there are many species of organisms capable of producing ammonia, the higher fungi

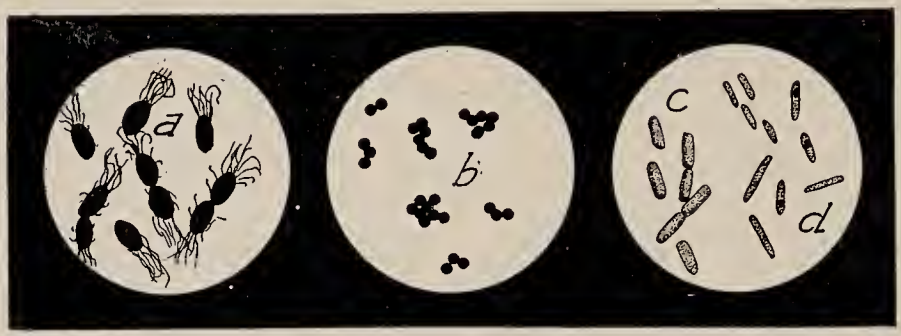


FIG. 58.—Some soil organisms important in the nitrogen cycle. (a) *Azotobacter agilis;* (b) nitrate bacteria. Urea bacteria, (c) *Urobacillus miguelii* and (d) *Urobacillus leubii.*

and algæ as well as bacteria participating in the change in the character of the nitrogen compounds.

Different soil organisms display diverse abilities in converting the nitrogen of the same organic material into ammonia, some acting more rapidly or more thoroughly than others. In tests by certain investigators in which the same bacteria were allowed to act on different substances, the order of their efficiency was reversed with a change of substance. This characteristic preference of a class of organisms for the decomposition of certain substances is made evident by the experiments of Sackett,[1] who found that in some soils dried

[1] Sackett, W. G., *The Ammonifying Efficiency of Certain Colorado Soils;* Colo. Agr. Exp. Sta., Bul. 184, 1912.

blood was ammonified more rapidly than was cottonseed meal, while in other soils the reverse was true.

While the soil fungi have been but little studied, the literature available seems to indicate that they take an important part in all soil processes, except possibly the fixation of atmospheric nitrogen and the formation of nitrates. Most soil fungi produce ammonia readily. Waksman [1] found such forms as *Mucor racemosus, Penicillium lilacinum, and Rhizopus sp. II* compared favorably in capacity to produce ammonia with *Bacillus mycoides* when grown in artificial culture, blood and cottonseed meal being the sources of nitrogen. Kopeloff [2] found that certain fungi seemed to prefer an acid medium for their ammonifying activities. This suggests that a natural provision is thus made for ammonification, no matter what the soil reaction may be.

Among the bacteria producing ammonification are *B. mycoides, B. subtilis, B. mesentericus vulgatus, B. janthinus,* and *B. proteus vulgaris.* Of these, *B. mycoides* has been very carefully studied, and the findings of Marchal [3] may be taken as representative of the process of ammonification. He found that when this bacterium was seeded on a neutral solution of albumin, ammonia and carbon dioxide were produced, together with small amounts of peptone, leucine, tyrosine, and formic, butyric, and propionic acids. He concludes that in the process atmospheric oxygen is used, and that the carbon of the albumin is converted into carbon doxide, the sulfur into sulfates, and the hydrogen partly into water, and partly into ammonia by combining with the nitrogen of the organic

[1] Waksman, S. A., *Soil Fungi and Their Activities;* Soil Sci., Vol. II, No. 2, pp. 103-155, 1916. See also, McLean, H. C., and Wilson, G. W., *Ammonification Studies with Soil Fungi;* N. J. Agr. Exp. Sta., Bul. 270, 1914.

[2] Kopeloff, N., *The Effect of Soil Reaction on Ammonification by Certain Soil Fungi;* Soil Sci., Vol. I, No. 6, pp. 541-573, 1916.

[3] Marchal, E., *Sur la Production de l'Ammoniaque dans le Sol par les Microbes;* Bulletins de l'Acad. Royale de Belg., 3 series, T. 25, pp. 727-776; 1893.

substance. Marchal found that *B. mycoides* was also capable of ammonifying casein, fibrin, legumin, glutin, myosin, serin, peptones, creatine, leucine, tyrosine, and asparagine, but not urea.

The following reactions may be cited as indicating the changes that probably occur when albumin and urea undergo ammonification:

$$\underset{\text{Albumin}}{C_{72}H_{112}N_{18}SO_{22}} + 77O_2 = 29H_2O + 72CO_2 + SO_3 + 18NH_3$$

$$\underset{\text{Urea}}{CON_2H_4} + 2H_2O = (NH_4)_2CO_3$$

While ammonification [1] seems to proceed to the best advantage in a well-drained and aërated soil with plenty of active basic material present, it will take place to some extent under almost any condition, due to the great number of different organisms capable of accomplishing the change. In certain soils, as shown by Russell and Hutchinson [2] as well as by other authors (see par. 211), protozoa may retard ammonification by feeding on the chief ammonia-producing organisms. Such a condition is seldom serious in arable soils.

[1] The ammonifying efficiency of a soil is usually determined by treating a 200-gram sample of fresh soil with cottonseed meal or dried blood carrying 120 milligrams of nitrogen. The mixture is then incubated, usually for seven days, at optimum temperature and moisture. The increase in ammonia is taken as a measure of the ammonifying efficiency. The artificial nature of the test detracts largely from its value. See Temple, J. C., *The Value of Ammonification Tests;* Ga. Agr. Exp. Sta., Bul. 126, 1919.

[2] Russell, E. J., and Darbishire, F. V., *Oxidation in Soils and Its Relation to Productiveness. Part 2. The Influence of Partial Sterilization;* Jour. Agr. Sci., Vol. 2, pp. 305-326, 1907.

Russell, E. J., and Hutchinson, H. B., *The Effect of Partial Sterilization of Soil on the Production of Plant Food;* Jour. Agr. Sci., Vol. 3, pp. 111-144, 1909.

Russell, E. J., and Hutchinson, H. B., *The Limitation of Bacterial Numbers in Normal Soils and Its Consequences;* Jour. Agr. Sci., Vol. 5, pp. 152-221, 1903.

Buddin, W., *Partial Sterilization of Soil by Volatile and Non-volatile Antiseptics;* Jour. Agr. Sci., Vol. 6, pp. 417-451, 1914.

229. Nitrification.—Some agricultural plants can utilize ammonium salts as a source of nitrogen.[1] This has been shown to be true for rice, maize, peas, barley, and potatoes (see par. 248). Most plants, however, except for rice, show a decided preference for nitrogen in the nitrate form. Whether these common crops can thrive as well on ammonium salts as on nitrates has not been definitely demonstrated. In most arable soils the transformation of nitrogen does not stop with its conversion into ammonia, but goes on by an oxidation process to the formation of nitrous acid. The nitrous acid, after reaction with a base, is farther oxidized, a salt of nitric acid resulting. This process of oxidation is generally spoken of as nitrification. The reactions involved may be written as follows:

$$2NH_3 + 3O_2 = 2HNO_2 + 2H_2O[2]$$
$$2HNO_2 + CaH_2(CO_3)_2 = Ca(NO_2)_2 + 2H_2O + 2CO_2[3]$$
$$Ca(NO_2)_2 + O_2 = Ca(NO_3)_2$$

Each of these steps is brought about by a distinct baeterium, but the groups are closely related. Collectively they are called nitrobacteria. Nitrosomonas and Nitrosococcus are the bacteria concerned in the conversion of ammonia into nitrous acid or nitrites. The former are supposed to be characteristic of European, and the latter of American, soils. The organisms concerned in the oxidation of nitrites to ni-

[1] Kelley, W. P., *The Assimilation of Nitrogen by Rice;* Haw. Agr. Exp. Sta., Bul. 24, 1911.

Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Centrlb. f. Bakt., II, Band 30, Seite 513-547, 1911.

[2] Loew states that the reaction is as follows:

$$2NH_3 + 2O_2 = 2HNO_2 + 4H$$

Loew, O., *Die Chemischen Verhältnisse des Bakterienlebens: II.* Centrlb. f. Bakt., II, Bd. 9, Seite 690-697, 1891.

[3] It has often been suggested that the acid produced by the nitrifying process is of considerable importance in rendering mineral nutrients available. While this may be true, the extent to which the solution phenomenon takes place and its practical significance have never been satisfactorily established by experimentation.

trates are generally designated as Nitrobacter. In practice these bacteria are generally spoken of as nitrite and nitrate organisms.[1] The conditions favoring the two groups are practically the same. As a consequence, nitrification is generally discussed as though the transformation was only one step and depended on one group of organisms.[2]

Just as ammonification follows closely on putrefaction, so nitrification closely accompanies the production of ammonia. In fact, the processes are so well synchronized in a normal soil that only traces of ammonia and nitrites are usually found. The nitrates, however, may accumulate in large amounts.

Marked differences have been noted in the nitrifying[3]

[1] While it was known from the middle of the nineteenth century that nitrogenous compounds added to the soil quickly produced nitrates, it was not until 1878 that Schlöessing and Müntz demonstrated that the process was biological. In 1890 Winogradsky succeeded in isolating the organisms. As they do not develop on ordinary medium, as do the decay and ammonifying bacteria, a special technique was necessary. Winogradsky used silicic-acid-gel plates containing certain inorganic salts, as he found that the presence of even small amounts of organic matter prevented the development of the organisms. In the soil, however, well-decayed organic matter generally stimulates rather than depresses nitrification. For a review of literature and methods of isolating nitrifying organisms, see Gibbs, W. M., *The Isolation and Study of Nitrifying Bacteria;* Soil Sci., Vol. VIII, No. 6, pp. 427-471, 1919.

[2] Kaserer has isolated an organism, which he called *B. Nitrator,* that can oxidize ammonia directly to nitrate. He writes the reaction as follows:

$$NH_3 + H_2CO_3 + O_2 = HNO_3 + H_2O + CH_2O.$$

He thinks that the energy necessary for the completion of the reaction is obtained from the formaldehyde (CH_2O) as follows:

$$CH_2O + O_2 = H_2O + CO_2 + \text{Energy}$$

The correlation between carbon dioxide production and nitrate accumulation lends probability to this theory.

Kaserer, H., *On Some New Nitrogen Bacteria with Autotrophic Habits of Life;* Noted in Exp. Sta. Record, Vol. 18, p. 534, 1905-1906.

[3] The nitrifying efficiency of a soil is usually determined by treating a 100-gram sample held in a tumbler with a suitable amount of ammonia sulfate or some other readily nitrifiable material. After incubation for a suitable period at optimum temperature and moisture, the increase of nitrate nitrogen is determined. This method is merely comparative and measures only the nitrate accumulation. Its value is limited as it does not simulate field conditions.

power of different soils. Highly productive soils have generally been found to maintain a greater nitrifying efficiency than less productive soils, but this is not always the case, as factors other than available nitrogen may limit the productiveness of a soil.

With the formation of nitrate nitrogen, the main portion of the nitrogen cycle is completed, since plants absorb most of their nitrogen as the nitrate ion. Of this cycle, from

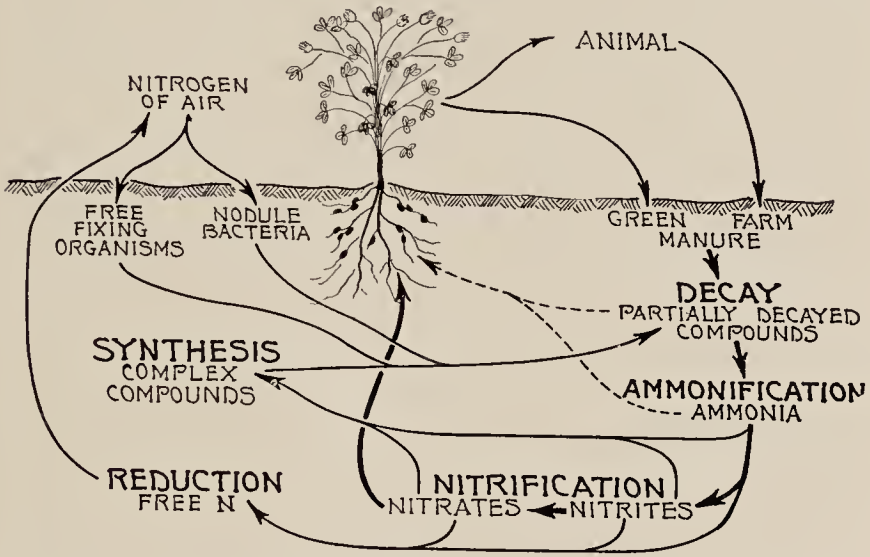


FIG. 59.—Diagram representing the movements of nitrogen between soil, plants, animals and the atmosphere. These transformations are termed the "nitrogen cycle."

plant to soil, and from soil to plant again, the nitrification reaction is the weakest point, since the other biological changes proceed to a certain extent in spite of unfavorable soil conditions. Nitrification is easily retarded and may even be brought to a standstill. As a consequence, the factors affecting this particular portion of the nitrogen cycle are of special interest. A soil favorable to nitrification is generally wholly favorable to the other desirable processes involving nitrogen transformations.

230. Relation of soil conditions to nitrification.—Although a very great number of factors influence the process of nitrification, the principal controls may be listed as follows: (1) presence of nitrifiable substance, (2) aëration, (3) temperature, (4) moisture, (5) soil reaction, and (6) the presence of soluble salts.

A peculiarity in the artificial cultivation of nitrifying bacteria is that they cannot be grown in artificial media containing organic matter. In the soil, however, organic matter, when well decayed, stimulates nitrification,[1] provided aëration and other conditions are favorable (see par. 313). The application of twenty tons of farm manure to the acre to sod on a clay loam soil for three consecutive years, at Cornell University,[2] resulted in a larger accumulation and probably a larger production of nitrates on the manured soils than on a contiguous plat of similar soil left unmanured. This was especially true during the third year of the application, when the land was in sod, and also during the fourth year, when no manure was applied to either plat and when both plats were planted to maize, as may be seen from Table XC (page 419).

These data indicate not only a marked influence of organic matter on nitrification but also an effect from aëration. Even allowing for a direct and differential influence on nitrification by the two crops, it is evident that tillage is a factor. Further experimental data from Cornell University may be quoted. Columns of soil eight inches in diameter and eight inches in depth were removed from a field of clay loam on the Cornell University farm and carried to the greenhouse without disturbing the original structure of the soil. At the same time, vessels of similar size were filled with soil dug from a spot near by. These may be termed unaërated and

[1] The turning under of a green-manuring crop generally depresses nitrification at first. Once the decay process is well under way, nitrification activities seem to be stimulated.

[2] Unpublished data. Cornell Agr. Exp. Sta., Ithaca, N. Y.

TABLE XC

NITRATE ACCUMULATION ON HEAVILY MANURED AND ON UNMANURED SOIL.

CROP	NO_3 IN PARTS TO A MILLION OF DRY SOIL	
	UNMANURED SOIL	TWENTY TONS MANURE TO THE ACRE FOR THREE YEARS
Timothy (3rd year)		
April 23rd	8.2	21.0
June 13th	.8	1.1
August 14th	1.8	3.0
Maize following timothy		
May 19th	17.5	20.1
July 6th	50.0	105.0
August 10th	151.0	184.0

aërated soils. Both were kept at the same temperature and moisture content in the greenhouse, but no plants were grown on them. The accumulation of nitrates was as follows:

TABLE XCI

TIME OF ANALYSIS	NITRATES, PARTS PER MILLION DRY SOIL	
	UNAËRATED SOIL	AËRATED SOIL
When taken from field	3.2	3.2
After standing one month	4.2	17.6
After standing two months	9.0	45.6

It has often been assumed that carbon dioxide is a detrimental factor in biological activity in two respects: by the replacement of oxygen and by a toxic influence on the organ-

isms. Recent experimentation,[1] however, indicates that carbon dioxide has little or no effect on nitrification and ammonification as long as appreciable quantities of oxygen are present. Aëration, insofar as most biological activities are concerned, has to do more with the presence of oxygen than the elimination of the carbon dioxide which is always forming.

Since aëration is such a factor in nitrification, the transformation is very largely confined to the surface layers of soil, except in the rich and porous subsoils of arid and semi-arid regions. The lack of nitrate formation in the lower depths is probably influenced by temperature as well as by lack of oxygen and organic matter. At 5° C. nitrification is very feeble. The optimum temperature seems to range from 25° to 30° C. The drainage of a soil probably promotes nitrification quite as much by facilitating a rise of temperature as by promoting the entrance of oxygen, especially in the spring.

The speed with which nitrification proceeds in a soil is governed to a marked extent by water content,[2] the process being retarded by both low and high moisture conditions. In practice, it is safe to assume that the optimum moisture as recognized for higher plants is optimum for nitrification

[1] Plummer, J. K., *Some Effects of Oxygen and Carbon Dioxide on Nitrification and Ammonification in Soils;* Cornell Agr. Exp. Sta., Bul. 384, 1916.

[2] Coleman, L. C., *Untersuchungen über Nitrifikation;* Centbl. f. Bakt., II, Bd. 20, Seite 401-420 and 484-513, 1908.

Fraps, G. S., *The Production of Active Nitrogen in the Soil;* Tex. Agr. Exp. Sta., Bul. 106, 1908.

Patterson, J. W., and Scott, P. R., *The Influence of Soil Moisture upon Nitrification;* Jour. Dept. Agr., Victoria, Vol. 10, pp. 275-282, 1912.

Stewart, R., and Greaves, J. E., *The Production and Movement of Nitric Nitrogen in Soil;* Centbl. f. Bakt., II, Bd. 34, Seite 115-147, 1912.

Gainey, P. L., *The Effect of Time and Depth of Cultivating a Wheat Seed-bed Upon Bacterial Activity in the Soil;* Soil Sci., Vol. II, No. 2, pp. 193-204, 1916.

also. Greaves and Carter [1] found that a moisture content of about 55 per cent. of the water-holding capacity, as determined by the Hilgard method (see par. 90), was especially favorable for nitrification.

It has generally been considered that nitrification was very much retarded if not actually brought to a standstill in an acid soil.[2] Recent data,[3] however, seem to indicate that the process will proceed in acid soil, although the addition of lime in some form is usually beneficial. The marked stimulation of liming to certain crops may be due partially to the influence of the lime on the nitrifying organisms. This relationship should be particularly noticeable if the crop in question is unable to utilize organic or ammoniacal forms of nitrogen.

The influence of certain mineral salts is quite significant.[4] Small amounts of salts, even those of manganese, stimulate the process. Sodium nitrate, unless applied in excessive amounts, promotes the nitrification of dried blood and cotton-seed meal. In general, the stimulation of soil bacteria by the application of fertilizer salts is coördinate with the stimulation ordinarily observed in higher plants. Rational fertilizer practice, therefore, promotes nitrification, and no important retarding influences may be expected on bacterial activity unless the crop is itself directly injured.

[1] Greaves, J. E., and Carter, E. G., *Influence of Moisture on the Bacterial Activities of the Soil;* Soil Sci., Vol. X, No. 5, pp. 361-387, 1920.

[2] Hall, A. D., *Fertilizers and Manure,* pp. 62-64, New York, 1909.

[3] Temple, J. C., *Nitrification in Acid or Non-basic Soils;* Ga. Agr. Exp. Sta., Bul. 103, 1914.

White, G. W., *Nitrification in Relation to the Reaction of the Soil;* Penn. Agr. Exp. Sta., Ann. Rep. 1913-14, pp. 70-84, 1916.

[4] Kelley, W. P., *Nitrification in Semiarid Soils;* Jour. Agr. Res., Vol. VII, No. 10, pp. 417-437, 1916.

Brown, P. E., and Hitchcock, E. B., *The Effect of Alkali Salts on Nitrification;* Soil Sci., Vol. IV, No. 5, pp. 207-229, 1917.

Brown, P. E., and Minges, G. A., *The Effect of Some Manganese Salts on Ammonification and Nitrification;* Soil Sci., Vol. II, No. 1, pp. 67-85, 1916.

231. Influences of higher plants on nitrification.—It has been known for some time that the nitrate content of a soil varies with the crop that occupies the land. King and Whitson [1] reported in 1901 that the accumulation of nitrates was greatest under maize, with potatoes next and alfalfa and clover much lower. Stewart and Greaves,[2] in an experiment covering several years, also found that maize allowed the greatest accumulation, with potatoes, oats, and alfalfa following in the order named. Brown and MacIntire [3] report forty times more nitrates in a soil cropped to maize than when planted to grass. As the moisture content was practically the same in each case, the difference cannot be ascribed to this influence.

Perhaps the most extensive work along this line is that of Lyon and Bizzell.[4] They noted a characteristic relationship between the crop at different stages of growth and the corresponding nitrate content of the soil. During the most active growing period of maize, although the crop was absorbing nitrogen in large amounts, the nitrates were frequently higher under the maize than in a contiguous fallow plat. Oat land contained less nitrates, while grass seemed to retard markedly the accumulation of nitrates. Whether the nitrate organisms are stimulated by certain plants or whether nitrate formation is merely depressed more by some plants than by others is not known. It is clear, however, that the relationship of crop to nitrification must be reckoned with in practical

[1] King, F. H., and Whitson, A. R., *Development and Distribution of Nitrates and Other Soluble Salts in Cultivated Soils;* Wis. Agr. Exp. Sta., Bul. 85, 1901.

[2] Stewart, R., and Greaves, J. E., *The Production and Movement of Nitric Nitrogen in Soil;* Centbl. f. Bakt., II, Band 34, S. 115-147, 1912.

[3] Brown, B. E., and MacIntire, W. H., *Seasonal Nitrification, Soil Moisture and Lime Requirement in Four Plats Receiving Sulfate of Ammonia;* Penn. Agr. Exp. Sta., Rep. 1909-1910, pp. 57-63.

[4] Lyon, T. L., and Bizzell, J. A., *Some Relations of Certain Higher Plants to the Formation of Nitrates in Soils;* Cornell Agr. Exp. Sta., Memoir 1, 1913.

soil management as well as the effect of nitrification on plant growth.

The influence of plants on nitrification is not confined to the period in which they are growing on the soil. Lyon and Bizzell, in the investigation previously mentioned, found that certain plants grew better when preceded by one species rather than by another. These authors, as already explained, have suggested that certain higher plants directly influence nitrification with varying intensity. The question now arises as to the possibility of such plants influencing the process of nitrate formation after their removal.

The following data from Lyon and Bizzell suggest that, while the effect is variable, plants seem definitely to influence the production of nitrates during the season after they have been removed. All of the plats were kept bare in 1911.

TABLE XCII

Treatment in 1910	Season 1910		Nitrates in Soil Kept Bare in 1911 Parts Per Million	
	Nitrates in Soil, Parts per Million, Seasonal Average	Nitrogen in Crop, Pounds Per Acre	May 1	June 28
Maize	167	3	52	37
Bare	136	—	50	35
Potatoes	104	43	28	26
Bare	108	—	43	32
Oats	90	29	22	22
Bare	126	—	36	33

These results indicate that maize exerts a stimulating influence during the following summer. Oats and potatoes seem to depress nitrate accumulation.

232. Relation of nitrification to soil fertility.—In spite of the immense amount of work that has been done on the bio-

logical problems of the soil, no definite relationships have been established between any given transformation and the productivity of the soil. General correlations have been repeatedly observed [1] but specific relationships, when recorded, are difficult to ascribe to other than chance concordance. Of all of the biological transformations, nitrification seems most likely to correlate with productivity, since most plants use large amounts of nitrate nitrogen.

Available data seem to show that there is a general correlation between the nitrifying capacity of soils and their crop-producing power.[2] Such a statement, however, does not imply that the productivity of soils, insofar as nitrogen is a limiting factor, is especially controlled by nitrification. Arable soils usually contain abundant nitrifying organisms, which seem to oxidize ammonia to the nitrate form as fast as it is produced. It would appear that nitrification is only one of the many factors that govern productivity, a high nitrate content of a soil accompanying, rather than controlling, high crop production.

233. Reduction of nitrates and allied compounds.—Nitrates may be removed from the soil in three ways: (1) by drainage, (2) by plant absorption, and (3) by reduction to free nitrogen. The loss of nitrogen by leaching and by cropping has already been adequately treated. It has been shown, for example (see par. 163), that as high a loss as 77 pounds of nitrogen to the acre a year may be expected from a heavy

[1] Ashby, S. F., *The Comparative Nitrifying Power of Soils;* Jour. Chem. Soc., London, Vol. 85, pp. 1158-1170, 1904.

Russell, E. J., and Hutchinson, H. B., *The Effect of Partial Sterilization of Soils on the Production of Plant Food;* Jour. Agr. Sci., Vol. III, pp. 111-144, 1909.

Kellerman, K. F., and Allen, E. R., *Bacteriological Studies of the Truckee-Carson Irrigation Project;* U. S. Dept. Agr., Bur. Plant Ind., Bul. 211, 1911.

Brown, P. E., *Relation Between Certain Bacterial Activities in Soils and Their Crop Producing Power;* Jour. Agr. Res., Vol. V, pp. 855-869, 1916.

[2] Gainey, P. L., *The Significance of Nitrification as a Factor in Soil Fertility;* Soil Sci., Vol. III, No. 5, pp. 399-416, 1917.

soil through the combined influence of cropping and drainage. This is equivalent to a removal of about 520 pounds of sodium nitrate as far as the nitrogen contained is concerned.

While the removal of nitrogen from the soil is due very largely to the phenomena just referred to, the loss of nitrogen through reduction demands a certain amount of attention. Reduction includes the change of nitrates to nitrites, to ammonia and even to free nitrogen.[1] In the same way nitrites may be reduced to ammonia and the latter to elemental nitrogen. When the process is carried to completion there is opportunity for an escape of some nitrogen to the atmospheric air. The loss of nitrogen is not the important consideration, however. The interference with plant nutrition, which naturally occurs, is much more serious and justifies the attention which the phenomena have received from bacteriologists.

The number of organisms that are capable of accomplishing one or more of the reduction processes is very large. This is due to the facultative character of the soil flora, which is able to alter its functions to suit the conditions. Thus *B. mycoides,* which is a normal decay and ammonifying organism, may, under anaërobic conditions become a vigorous reducing agent. Other specific reducing organisms are:—*B ramosus and B. pestifer, B. subtilis, B. mesenterious vulgatus, B. denitrificans,* and many others. It is probable that fungi also are able to effect the transformation.

Most of the reducing bacteria perform their functions only in presence of a limited amount of oxygen, while others can operate in the presence of a more liberal supply. In general, thorough aëration of the soil impedes the process to a considerable degree. Straw apparently carries an abundant supply of such organisms, and it is consequently possible to reach a

[1] The reaction may be illustrated empirically as follows:

$$2HNO_3 = 2HNO_2 + O_2.$$
$$4HNO_2 = 2H_2O + 2N_2 + 3O_2.$$
$$HNO_3 + H_2O = NH_3 + 2O_2.$$

point in manuring at which reduction takes place. When fifty tons or more of farm manure, in addition to a nitrate fertilizer, are added to the soil, unfavorable reactions may occur. Plowing under heavy crops of green-manure may produce the same result. In either case the best way to overcome the difficulty is to allow the organic matter partly to decompose before adding the fertilizer. The removal of the easily decomposable carbohydrates needed by the reducing organisms decreases or precludes their activity in this direction.

Under ordinary farm conditions conversion to free nitrogen is of no significance in the soil where proper drainage and good tillage are practiced. Warington [1] showed that if an arable soil is kept saturated with water to the exclusion of air, nitrates added to the soil are decomposed, with the evolution of nitrogen gas. As lack of drainage is usually most pronounced in early spring, when the soil is likely to be depleted of nitrates, it is not likely that much loss occurs in this way unless a nitrate fertilizer has been added. Among the many difficulties arising from poor drainage the reduction of an expensive fertilizer may be no inconsiderable item.

234. Assimilation of nitrates and allied compounds.[2]— In addition to the nitrate-reducing organisms already mentioned, there are other bacteria and fungi that utilize nitrates, nitrites, and ammonia. Like higher plants, they convert the nitrogen into organic nitrogenous substances. The process is therefore, one of synthesis, rather than of reduction although reduction often occurs at the beginning of the process. As such organisms operate in the dark, they must have organic acids or carbohydrates as a source of energy. This means of nitrate disappearance is probably of much more

[1] Warington, R., *Investigations at Rothamsted Experimental Station;* U. S. Dept. Agr., Office of Exp. Sta., Bul. 8, p. 64, 1892.

[2] The term denitrification is often used in referring to the reduction and assimilation of nitrates and allied compounds in the soil. The word is so loosely used in soil literature that it has seemed best to ignore it, at least for the present.

practical importance than nitrate reduction, yet even less is known regarding the phenomena. Many different forms of bacteria and fungi are probably capable of assimilating nitrogen, but what conditions favor their activity in this respect cannot be stated definitely.[1] To make the problem more intricate higher plants seem to be a factor to a certain extent in this type of nitrate disappearance. Seasonal influences also have been noted, which suggest the possibility of a special nitrate assimilating flora.

Nitrate accumulation always proceeds slowly on sod land, especially if the soil is heavy. Lack of sufficient moisture or unfavorable temperature relations do not always adequately account for this phenomenon. An experiment at Cornell University [2] is typical of the conditions mentioned above. In this case, maize and grass were grown side by side, the nitrates being determined at frequent intervals during the season. The nitrates are expressed in parts per million of dry soil for the various months.

TABLE XCIII

NITRATES IN PARTS PER MILLION UNDER MAIZE AND SOD. CORNELL UNIVERSITY.

Month	Nitrates, Parts per Million Dry Soil	
	Sod Land	Maize Land
April	8.9	——
May	3.0	17.1
June	2.4	40.3
July	4.0	194.0
August	5.4	186.7

[1] Murray has found at the Washington Agricultural Experiment Station that the addition of straw to the soil markedly aided the bacterial utilization of nitrates. The numbers of bacteria increased without reference to the groups present.

Murray, T. J., *The Effect of Straw on the Biological Soil Processes;* Soil Sci., Vol. XII, No. 3, pp. 233-259, 1921.

[2] Unpublished data. Cornell Agr. Exp. Sta., Ithaca, N. Y.

The high nitrate accumulation under the maize is probably due to the tillage and aëration which the soil received and possibly to the direct stimulation of the crop on nitrification. The low amounts of nitrate nitrogen in the grass land are probably due, at least partially, to the influence of the sod in encouraging nitrate assimilation by the soil organisms. The nitrifying power of the sod soil is probably much greater than the data just presented would lead one to suspect. Sodium nitrate applied to grass at Cornell University was found to be changed to other than the nitrate form very rapidly, even when the amounts added were extremely large. This rapid disappearance of the nitrate form of nitrogen is not readily accounted for by cropping and drainage removal. Such facts lend considerable plausibility to the suggestions made above, regarding the encouragement which the synthetic removal, especially of nitrates, receives from organisms when the soil is under a grass crop.

The synthetic removal of nitrates, nitrites, and ammonia assumes considerable importance at certain times of the year. It seems to be a natural means of conserving an important soil constituent, since nitrate nitrogen is extremely soluble and easily lost by drainage. The nitrogen thus affected is changed to a more or less stable form, from which nitrates may be produced during the following year. The use of a cover-crop in an orchard during the late summer and fall is often practiced. A disappearance of nitrates but not a loss of nitrogen thus occurs and the trees are early forced into the resting stage.

235. Natural acquisition of nitrogen by the soil.—Since all of the nitrogen now found in the soil was probably acquired from the atmosphere, the natural forces which facilitate such a transfer assume considerable practical importance. The more rapid the natural acquisition of nitrogen from the air, the less serious will be the nitrogen problem in agricultural practice.

Three modes of nitrogen fixation are usually recognized: (1) rain-water additions, (2) the action of soil organisms functioning independently of living higher plants, and (3) the influence of organisms functioning parasitically or symbiotically in the soil.

236. Additions of nitrogen in rainwater.—Nitrogen occurring in rainwater is generally in the nitrate and ammonical forms and, consequently, is readily available to plants. The amounts thus brought down are quite variable, usually fluctuating markedly with season and location. The following table gives some of the more important findings regarding the amount of nitrogen thus added to the soil in various parts of the world.

TABLE XCIV

LOCATION	YEARS OF RECORD	RAINFALL IN INCHES	POUNDS TO THE ACRE A YEAR	
			AMMONIACAL NITROGEN	NITRATE NITROGEN
Harpenden, England [1]	28	28.8	2.64	1.33
Garford, England [2]	3	26.9	6.43	1.93
Flahult, Sweden [3]	1	32.5	3.32	1.30
Groningen, Holland [4]	—	27.6	4.54	1.46
Bloemfontein and Durban, S. Africa [5]	2	——	4.02	1.39
Ottawa, Canada [6]	10	23.4	4.42	2.16
Ithaca, New York [7]	6	29.3	11.50	1.01

[1] Russell, E. J., and Richards, E. H., *The Amount and Composition of Rain Falling at Rothamsted;* Jour. Agr. Sci., Vol. IX, pp. 309-337, 1919.

[2] Crowther, C., and Ruston, A. G., *The Nature, Distribution and Effects upon Vegetation of Atmospheric Impurities In and Near an Industrial Town;* Jour. Agr. Sci., Vol. IV, pp. 25-55, 1911.

[3] Von Feilitzen, H., and Lugner, I., *On the Quantity of Ammonia and Nitric Acid in Rainwater Collected Near Flahult, in Sweden;* Jour. Agr. Sci., Vol. III, pp. 311-313, 1910.

[4] Hudig, J., *The Amounts of Nitrogen as Ammonia and Nitric Acid*

Apparently the ammoniacal nitrogen is always considerably larger in amount than that in the nitrate form. It is also noticeable that while the nitrate nitrogen is about the same for every station, the nitrogen in the form of ammonia shows wide variations. The quantities at Ithaca, New York, are considerably larger than those from any other station. Considering the figures as a whole, it seems fair to assume that on the average about 4½ pounds of ammoniacal and 1½ pounds of nitrate nitrogen fall on every acre of soil yearly in rainwater. Assuming that all of this nitrogen passes into the soil, an average gain to the acre of 6 pounds of nitrogen may be expected.

It is interesting at this point to compare such a gain with the annual loss of nitrogen from the soil. The removal of nitrogen from the Cornell lysimeter soils (see par. 163), through drainage and cropping combined, amounted to 69.0, 77.8 and 56.9 pounds yearly to the acre, respectively, for a bare soil, one carrying a standard rotation, and one continuously in grass. While a gain of 6 pounds to the acre yearly seems rather insignificant in comparison to these figures, such an addition is of considerable importance over a period of years, and has had much to do with the accumulation of the nitrogen of our arable soils. Such a gain is equivalent in a practical way to the addition of about 40 pounds of commercial sodium nitrate to the acre yearly.

237. Acquisition of nitrogen by free-fixing organisms.— While it has long been known that the soil contains a great variety of organisms, it is only in recent years that it has been

in the Rainwater Collected at Uithuizer-Meeden, Gronigen; Jour. Agr. Sci., Vol. IV, pp. 260-269, 1912.

[5] Juritz, C. F., *Chemical Composition of Rain in the Union of South Africa;* S. Africa Jour. Sci., Vol. 10, pp. 170-193, 1914.

[6] Shutt, F. T., and Dorrance, R., *The Nitrogen Compounds of Rain and Snow;* Proc. and Trans. Roy. Soc. Canada, Vol. XI, No. 3, pp. 63-71, 1917.

[7] Wilson, B. D., *Nitrogen in the Rainwater at Ithaca, New York;* Soil Sci., Vol. XI, No. 2, pp. 101-110, 1921.

definitely shown that certain of these organisms have the power of utilizing atmospheric nitrogen, which later becomes a part of the nitrogenous matter of the soil. Boussingault [1] in 1858 suggested the possibility of such a phenomenon, but it was not until 1883 that Berthelot [2] began experiments by which he demonstrated that bare soils appreciably increase in nitrogen on exposure under such conditions. Winogradski [3] in 1894 was the first, however, to isolate an organism capable of affecting such a transformation. This bacterium was an anaërobic, rod-shaped organism producing spores and a boat-shaped mass (clostridium); hence the name, *Clostridium pastorianum*. It is very widely distributed in soils.

The most important organism fixing nitrogen independently in the soil was discovered by Beijerinck [4] in 1901. This organism was an aërobic bacillus to which he gave the name Azotobacter. It was at first thought that this bacillus could not fix nitrogen unless certain other organisms, such as Granulobacter, Radiobacter and Aërobacter, were also present. Lipman [5] has shown this idea to be erroneous, although the efficiency of Azotobacter is much higher in mixed than in pure cultures. A number of different species of Azotobacter have been studied, the *A. chroöcoccum* apparently being the most widespread.

Clostridium pastorianum and Azotobacter are by no means the only soil organisms capable of fixing nitrogen. Among

[1] See Voorhees, E. B., and Lipman, J. G., *A Review of Investigations in Soil Bacteriology;* U. S. Dept. Agr., Office of Exp. Sta., Bul. 194, 1907.

[2] Berthelot, M., *Recherches nouvelles sur les microorganisms fixateurs de l'azote;* Compt. Rend. Acad. Sci. Paris, Tome 115, pp. 569-574 and 842-849, 1892-93.

[3] Winogradsky, S., *Sur l'assimilation de l'azote gazeux de l'atmosphere par les microbes;* Compt. Rend. Acad. Sci. Paris, Tome 118, pp. 353-355, 1894.

[4] Beijerinck, M. W., *Über Oligonitrophile Mikroben;* Centrbl. Bakt., II, Bd. 7, S. 561-582, 1901.

[5] Lipman, J. G., *Experiments on the Transformation and Fixation of Nitrogen by Bacteria;* N. J. Agr. Exp. Sta., 24th Ann. Rep., pp. 217-285, 1903.

bacteria, *B. mesentericus, B. pneumoniæ, B. radiobacter, B. amylobacter, B. prodigiosus, B. asterosporus,* and *B. lactis viscusus* have certain capacities in this direction. Duggar and Davis[1] have shown that certain filamentous fungi, such as *Phoma betæ, Aspergillus niger, Pencillium digitatum,* and others have the ability of utilizing atmospheric nitrogen. The power of fixing nitrogen is, therefore, possessed by a large number of different organisms, yet from the data now at hand the Azotobacter group seems to be of the greatest economic importance. The nitrogen fixed enters the nitrogen cycle when the organisms die, undergoing decay, ammonification and nitrification, thus becoming available to higher plants.

238. Conditions for azofication and the amount of nitrogen fixed.[2]—The term azofication relates to the fixation of nitrogen by the Azotobacter group, although it may be used loosely in reference to all free-fixing activities. The soil conditions favorable to this phenomenon are those which are optimum for higher plants. This is especially true regarding aëration, temperature, and moisture relations. The process is encouraged by the application of lime when soils are acid and seem to require considerable phosphorus. This element is probably utilized in building up proteins within the bodies of the organisms. Potassium, sulfur, iron, and magnesium seem also to be essential to the phenomenon. The Azotobacter themselves are influenced by catalytic agents such as manganese.

Since considerable energy is required for nitrogen fixation the presence of organic matter in the soil becomes very important in this regard. Almost any non-toxic organic material may serve as a source of energy, even cellulose being very effective. Farm manure seems especially to encourage

[1] Duggar, B. M., and Davis, A. R., *Studies in the Physiology of the Fungi;* Ann. Mo. Bot. Garden, Vol. 33, pp. 413-437, 1916.

[2] A very excellent review of literature and discussion of Azofication: Greaves, J. E., *Azofication;* Soil Sci., Vol. VI, No. 3, pp. 163-217, 1918.

nitrogen fixation. The maintenance of a fair supply of soil organic matter is, therefore, as important as the regulation of the temperature, the oxygen, the moisture, and the reaction of the soil. While the presence of nitrates in small amounts seems to stimulate azofication, large quantities of nitric nitrogen tend to lessen nitrogen fixation.

The amount of nitrogen fixed in the soil by organisms functioning independently of higher plants is, as might be expected, a variable quantity. Hall [1] considers it to be on the average about 25 pounds yearly to the acre, Greaves [2] 25 pounds, Löhnis [3] 36 pounds, and Lipman [4] from 15 to 40 pounds. As a basis for calculation 25 pounds is perhaps a conservative and reasonable figure. A comparison of this figure with the 6 pounds of nitrogen brought down yearly in rain-water, indicates that the free-fixing organisms are four or five times more important than rainfall as a source of nitrogen.

239. Bacillus radicicola and its relationship to the host plant.—It has long been recognized by farmers that certain crops, as clover, alfalfa, peas, beans, and some others, improve the soil, making it possible to grow larger crops of cereals after these plants have occupied the land. Within the last century the benefit has been traced to the fixation of nitrogen through the agency of bacteria contained in nodules on the roots. The specific plants so affecting the soil were found to be, with a few exceptions, those belonging to the family of legumes. It has furthermore been demonstrated that the host plant is generally able to appropriate some of the nitrogen so fixed and thus benefit by the relationship. The phenomenon was fully explained in 1886 by Hellreigel

[1] Hall, A. D., *On the Accumulation of Fertility by Land Allowed to Run Wild;* Jour. Agr. Sci., Vol. I, pp. 241-249, 1905.

[2] Greaves, J. E., *Azofication;* Soil Sci., Vol. VI, No. 3, pp. 163-217, 1918.

[3] Löhnis, F., and Westermann, F., *Über Stickstoff fixierende Bakterien,* IV. Centrbl. f. Bakt., II, Bd. 22, S. 234-254, 1909.

[4] Lipman, J. G., *Marshall's Microbiology,* p. 343, 1917.

and Wilfarth. The organisms, of which there are a number of strains, are called *Bacillus radicicola.*

The organisms living in the root nodules take free nitrogen from the air in the soil, and the host plant secures it in some form from the bacteria or their products. The presence of a certain species of bacteria is necessary for the formation of tubercles. Leguminous plants grown in cultures or in soil not containing the necessary bacteria do not form nodules and do not utilize atmospheric nitrogen, the result being that the crop produced is less in amount and the percentage of nitrogen in the crop is lower than if nodules were formed.

The nodules are not normally a part of leguminous plants, but are evidently caused by an irritation of the root surface, much as a gall is caused to develop on a leaf or a branch of a tree by an insect. In a culture containing the proper bacteria the prick of a needle on the root surface will cause a nodule to form in the course of a few days. The entrance of the organism is effected through a root-hair which it penetrates, and it may be seen as a filament extending the entire length of the hair and into the cortex cells of the root, where the growth of the tubercle starts.

Even where the causative bacteria occur in cultures or in the soil, a leguminous plant may not secure any atmospheric nitrogen, or perhaps only a small quantity, if there is an abundant supply of readily available combined nitrogen on which the plant may draw. The bacteria have the ability to utilize combined as well as uncombined nitrogen, and prefer to have it in the former condition. On soils rich in nitrogen, legumes may, therefore, add little or no nitrogen to the soil, if the above ground portion of the crop is not plowed under; while in properly inoculated soils deficient in nitrogen an important gain of nitrogen may result.

While *B. radicicola* is considered the organism common to all leguminous plants, it is now known that the organisms from one species of legume are not equally well adapted to

the production of tubercles on other leguminous species. Certain cross inoculations are, however, very successful. The organisms seem to be interchangeable within the clovers, the vetches and the bean family. The organisms from sweet clover and burr clover will inoculate alfalfa, while the bacteria may be transferred from vetch to field pea or from cowpea to velvet bean.

It has been shown by several investigators that bacteria from the nodules of legumes are able to fix atmospheric nitrogen even when not associated with leguminous plants. There would seem to be no doubt, therefore, that the fixation of nitrogen in the tubercles of legumes is accomplished directly by this organism, not by the plant itself nor through any combination of the plant and the organism. The relationship is, therefore, parasitical rather than strictly symbiotic, although the host plant benefits from the relation. The part played by the plant is doubtless to furnish the carbohydrates which are required in considerable quantities by all nitrogen-fixing organisms and which the legumes are able to supply in large amounts. The utilization of large quantities of carbohydrates by the nitrogen-fixing bacteria in the tubercles may also account for the small proportion of non-nitrogenous organic matter in the plants.

How the plant absorbs this nitrogen after it has been secured by the bacteria is not well understood nor is it known in exactly what form the nitrogen is at first fixed, although amino and amide nitrogen very soon appear.[1] Early in the growth of the tubercle, a mucilaginous substance is produced, which permeates the tissues of the plant in the form of long slender threads containing the bacteria. These threads develop by branching or budding, and form what have been called Y and T forms, known as bacteroids, which are peculiar to these bacteria. The threads finally disappear, and the

[1] Strowd, W. H., *The Forms of Nitrogen in Soybean Nodules;* Soil Sci., Vol. XI, No. 2, pp. 123-130, 1921.

bacteria diffuse themselves more or less through the tissues of the root. What part the bacteroids play in the transfer of nitrogen is not known. It has been suggested that in this form the nitrogen is absorbed by the tissues of the plant. It seems quite likely that the nitrogen compounds produced within the bacterial cells are diffused through the cell-wall and absorbed by the plant.

240. The practical importance of B. radicicola.—The nitrogen fixed by the nodule organisms may go in three directions in the soil. It may be absorbed by the host plant, the latter benefiting greatly by the association. This relationship has already been discussed. Secondly, the nitrogen may pass in some way into the soil itself and benefit a crop associated with the legume. Thirdly, the nodules may decay, when the legume dies or is turned under, the nitrogen becoming available to the succeeding crop.

The relationship between associated legumes and non-legumes has been particularly studied by Lyon and Bizzell [1] and by Lipman.[2] It has been quite definitely proven that the non-legume may be greatly benefited by the association under some conditions. This accounts for the practice of growing timothy with clover, which has been common for centuries. Just how the transfer of nitrogen is facilitated yet remains to be shown.

The beneficial influences of such legumes as clover, vetch, and alfalfa on the succeeding crops has long been taken advantage of in practical agriculture. Until recently the stimulation has been ascribed to an actual increase of nitrogen in the soil, due to the growth of the legume and the activity of its nodule organisms. This will not always account for the phenomenon, since it has been shown by a number of investi-

[1] Lyon, T. L., and Bizzell, J. A., *Availability of Soil Nitrogen in Relation to the Basicity of the Soil and to the Growth of Legumes;* Jour. Ind. and Eng. Chem., Vol. 2, No. 7, pp. 313-315, 1910.

[2] Lipman, J. G., *The Associative Growth of Legumes and Non-Legumes.* N. J. Agr. Exp. Sta., Bul. 253, 1912.

gators that the continuous growing of legumes, the tops being removed as forage, does not always increase the nitrogen content of the soil to any greater extent than does a non-leguminous crop.

The results of Swanson [1] are particularly striking in this respect. This investigator sampled a number of fields in Kansas that had grown alfalfa continuously for twenty or thirty years, at the same time obtaining soil from contiguous native sod. In most cases the alfalfa soil was lower in nitrogen than the sod. Lyon and Bizzell [2] found practically the same content of nitrogen in contiguous alfalfa and timothy soils after the crops had been growing six years. The maize crop following the alfalfa was nevertheless much greater than that after the timothy. Since the soil on which a legume has been growing generally has a rather high nitrifying capacity,[3] the explanation seems to lie in the ready availability of the nitrogen in the soil which bore the legume, rather than to the presence of an especially large amount.

The amount of nitrogen fixed by the nodule organisms of a leguminous crop is very uncertain. If the soil is acid, if it contains alkali salts above a certain amount, or if nitrates develop rapidly, nitrogen fixation is markedly retarded. Much also depends on the virulence of the organisms, the character of the legume, the presence of organic matter, and other important conditions. Hopkins [4] estimates that about one-third

[1] Swanson, C. O., *The Effect of Prolonged Growing of Alfalfa on the Nitrogen Content of the Soil;* Jour. Amer. Soc. Agron., Vol. 9, No. 7, pp. 305-314, 1917.

Swanson, C. O., and Latshaw, W. L., *Effect of Alfalfa on the Fertility Elements of the Soil in Comparison with Grain Crops;* Soil Sci., Vol. VIII, No. 1, pp. 1-39, 1919.

[2] Lyon, T. L., and Bizzell, J. A., *Experiments Concerning the Top-dressing of Timothy and Alfalfa;* Cornell Agr. Exp. Sta., Bul. 339, pp. 136-139, 1913.

[3] Lyon, T. L., Bizzell, J. A., and Wilson, B. D., *The Formation of Nitrates in a Soil Following the Growth of Red Clover and of Timothy;* Soil Sci., Vol. IX, No. 1, pp. 53-64, 1920.

[4] Hopkins, C. G., *Soil Fertility and Permanent Agriculture,* p. 223, Boston, 1910.

of the nitrogen of a normal inoculated legume comes from the soil and two-thirds from the air. He also assumes that one-third of the nitrogen of the plant exists in the roots. Although both of these assumptions are questionable, they suggest the reason why the removal of the tops of legumes as forage allows no accumulation of nitrogen in the soil.

According to Hopkins, the nitrogen in the tops of legumes is a rough measure in general of the nitrogen fixed. On such an assumption, the growth of red clover should facilitate the fixation of about 40 pounds of nitrogen for every ton of air-dry material. On the same basis, the figure should be about 50 pounds for alfalfa, 43 pounds for cowpeas, and 53 pounds for soybeans. These figures, even though they are obviously incorrect, give some idea of the importance of *B. radicicola* in nitrogen fixation. The growth of an average leguminous crop under proper conditions probably is accompanied by a fixation of 80 to 100 pounds of nitrogen. Of the three natural methods by which atmospheric nitrogen may be fixed by the soil that facilitated by the nodule organisms seems at first thought to be considerably the most important. It must be remembered, however, that with an average rotation a legume occupies the land but one or two years in three to six. Moreover, the gain of nitrogen in a fertile soil is but slight unless the crop is turned under as a green-manure. Unless so used the chief advantages of growing a leguminous crop lie in the increase of soil organic matter, the ready and favorable decay of the roots and stubble, and the opportunity of growing a high protein crop without materially depleting the soil nitrogen.

241. Soil inoculation for legumes.—Although the inoculation of the soil with free-fixing organisms has not proven of value, since such organisms are always present and sufficiently active if soil conditions are favorable, the inoculation with nodule bacteria is of considerable practical importance. Such organism may never have been present in a soil or may

have disappeared because of unfavorable conditions. If legumes, especially of certain types, are to be grown most successfully, the specific strains of *B. radicicola* for that crop must be present.

Two general methods of inoculation are available: (1) the use of soil from fields where the particular legume in question is growing or has grown successfully; and (2) the utilization of artificial cultures of some form. *Bacillus radicicola* is found in the soil as well as in the plant nodules. As a matter of fact, this bacterium will live in the soil for long periods, even if the host plant is not grown. Whether it fixes nitrogen to any extent under such conditions is a question. At least the organism does not lose its virulence. Such soil may be spread on the land to be inoculated at the rate of 300 to 500 pounds to the acre. It should be applied in the evening or on a cloudy day and harrowed in as soon as possible, as the organisms are injured by direct sunlight.

The soil carrying the organism may also be mixed after air-drying with the seed, the latter having been moistened with a dilute glue solution.[1] Enough of the dry earth sticks to the seed to carry the organisms into the soil. The advantage of this method is that the bacteria are in contact with the seed and the plants become infected very soon after the seeds germinate. The main objection to the soil method of inoculation lies in the possibility of spreading plant diseases and undesirable weeds.

[1] Dissolve ordinary furniture glue in boiling water, two handfuls of glue to every gallon of water used, and allow the solution to cool. Put the seed in a wash-tub, and then sprinkle enough of the solution on the seed to moisten but not to wet it (one quart to a bushel is sufficient), and stir the mixture thoroughly until all the seeds are moistened.

Dry the inoculating soil in the shade, preferably in the barn or basement, and pulverize it thoroughly into a dust. Scatter this dust over the moistened seed, using from one-half to one gallon of dirt for each bushel of seed, mixing thoroughly until the seed no longer stick together. The seed is then ready to sow.

See Vrooman, C., *Grain Farming in the Corn Belt with Live Stock as Side Line;* Farmers' Bul., No. 704, 1916.

Within recent years a number of cultures for soil inoculation have been offered to the public. The first of these utilized absorbent cotton to transmit the bacteria in a dry state from the pure culture in the laboratory to the user of the culture, who was to prepare therefrom another culture to be used for inoculating the soil. Careful investigation of this method showed that its weakness lay in drying the cultures on the absorbent cotton, which frequently resulted in the death of the organisms. More recently liquid cultures have been placed on the market in this country, and these have, in the main, proved to be more successful, notably those sent out by the United States Department of Agriculture.

Another very successful culture medium, now being used by the Department of Plant Physiology at Cornel University, is steamed soil. A soil, favorable to the development of nodule organisms and usually a sandy loam, is sterilized by steaming. It is then brought up to optimum moisture and later inoculated with a number of different strains of *B. radicicola*. After incubation for several days at a favorable temperature, the soil cultures are ready for distribution. The soil is sent out in small air-tight cans by parcel post. The advantage of such a culture is that the organisms are virulent and there is no danger from plant diseases or undesirable weeds.

When a culture of this sort is received it may be used in a number of different ways. It may be mixed with field soil at the rate of 1 pound to 300 of the latter. This 300 pounds of inoculated soil may then be spread on a acre of land in the usual way. The culture may also be disposed of by the glue method or it may be suspended in water and the extract sprinkled on the seed and dried in the shade. In either case, the seed should be sown as soon as possible.

242. Resume.—The biological phases of the soil are so numerous and far-reaching that it is obviously impossible in summarizing their practical relationships to do more than call

attention to certain significant facts. In the first place, the soil fauna and flora, especially the latter, are exceedingly complex. The number of plant forms are so numerous that the discussion already presented serves as little more than an introduction. In the second place, the transformations facilitated by soil organisms involve all of the normal constituents of the soil, both organic and inorganic. Moreover, biological activities determine to a large degree the efficacy of every addition, natural or artificial, made to the land. While the cycles generally recognized are apparently clear cut, the transformations themselves are actually involved in intricacies, which man will probably never entirely unravel.

A third phase of outstanding importance is the relationship of the biological activities of the soil to the nitrogen problem. Not only are the complex nitrogenous compounds of the soil readily made available to higher plants by soil organisms, but means are provided whereby considerable nitrogen, inert as it is, may be wrested from the atmosphere and forced into activity within the soil. It is not impossible that in certain favored cases 150 pounds of nitrogen to the acre may be yearly added to the soil by such processes. This phase alone is worthy of the most careful practical study. Obviously no system of soil management can be wholly successful unless full advantage is taken of this and other biological possibilities of the land.

CHAPTER XXII

COMMERCIAL FERTILIZER MATERIALS[1]

While the use of animal excrement on cultivated soils was practiced as far back as systematic agriculture can definitely be traced, the earliest record of the use of mineral salts for increasing the yield of crops was published in 1669 by Sir Kenelm Digby.[2] He says: "By the help of plain salt petre, diluted in water, and mingled with some other fit earthly substance, that may familiarize it a little with the corn into which I endeavored to introduce it, I have made the barrenest ground far outgo the richest in giving a prodigiously plentiful harvest." His dissertation does not however, show any true conception of the reason for the increase in the crop through the use of this fertilizer. In fact, the lack of any real knowledge at that time of the composition of the plant would have made this impossible.

In 1804, de Saussure,[3] a Frenchman, called attention, for the first time to the significance of the ash ingredients of plants not only showing that these mineral materials were

[1] The following general references may prove helpful:
Hall, A. D., *Fertilizers and Manure;* New York, 1921.
Halligan, J. E., *Soil Fertility and Fertilizers;* Easton, Pa., 1912.
Van Slyke, L. L., *Fertilizers and Crops;* New York, 1912.
Fraps, G. S., *Principles of Agricultural Chemistry;* Easton, Pa., 1912.
Collins, S. H., *Chemical Fertilizers and Parasiticides;* New York, 1920.

[2] Digby, Kenelm, *A Discourse Concerning the Vegetation of Plants;* London, 1669.

[3] Saussure, Theodore de, *Recherches Chimiques sur la Vegetation;* Paris, 1804.

obtained from the soil but pointing out that they were absolutely essential for plant growth. Liebig,[1] in Germany, at about the middle of the nineteenth century, emphasized still more strongly the importance of minerals to plants, refuting the theory, at that time current, that plants obtained all of their carbon from the soil organic matter. While he showed the importance of potash and phosphoric acid in manures, he failed to appreciate the value of nitrogenous materials, holding that the soil received sufficient ammonia in rain-water. The true conception of the necessity of supplying nitrogen in some form was definitely established in an experimental way in 1857 by Lawes, Gilbert and Pugh [2] of the Rothamsted Experiment Station, England. The extreme care used by these investigators caused them to sterilize the soil with which they were working. They thus failed to discover the utilization of free atmospheric nitrogen by legumes. This phenomenon, so important in practical agriculture, was explained by Hellriegel and Wilforth in 1886.

Between 1840 and 1850 Sir John Lawes placed the manufacture of superphosphates on a commercial basis by treating bones and coprolites with sulfuric acid. At about this time the importation into Europe of Peruvian guano and sodium nitrate began. The commercial fertilizers industry, which has now attained such importance in practical agriculture, may be considered as dating from this period.

243. Commercial fertilizers.—Although the commercial fertilizer industry is but little more than seventy years old, the sale of fertilizers in this country at the present time amounts to millions of dollars annually. Animal refuse and

[1] Liebig, J. Justus von, *Principles of Agricultural Chemistry with Special Reference to the Late Researches Made in England;* London, 1855. Also, *Chemistry in Its Applications to Agriculture and Physiology;* New York, 1856.

[2] Lawes, J. B., Gilbert, J. H., and Pugh, E., *On the Sources of the Nitrogen of Vegetation, with Special Reference to the Question Whether Plants Assimilate Free or Uncombined Nitrogen;* Rothamsted Memoirs, Vol. 1, No. 1, 1862.

phosphates are exported, while sodium nitrate and potash salts are imported in large amounts. Fifty per cent. of the fertilizers sold in the United States are applied in the south Atlantic states within three or four hundred miles of the seaboard. Nearly one-half of the remainder is purchased by the New England and middle Atlantic states. West of the Mississippi River, the use of fertilizers, especially those carrying phosphoric acid, is increasing rapidly.

The primary function of a commercial fertilizer is to supply plant nutrients to the soil in such a form that the plant may be directly influenced by such an application. The secondary influences of fertilizers may be beneficial or detrimental. The exact nature of the secondary influences depends on the particular fertilizer applied and especially on the type of soil and the crop management in vogue.

Prepared fertilizers, as found on the market, are usually composed of a number of ingredients. Since these ingredients are the carriers of the nutrient constituents, and since it is on their composition and solubility that the value of a fertilizer depends, a knowledge of the properties of these materials is not only of interest to every one who uses fertilizers but is also a valuable aid in their purchase.

FERTILIZERS USED FOR THEIR NITROGEN

Nitrogen is usually the most expensive constituent of manure and is of great importance, since it is very likely to be deficient in soils. A commercial fertilizer may have its nitrogen in the form of soluble inorganic salts or in organic combination. On the form depends to a certain extent the agricultural value of the nitrogen, as the soluble inorganic salts are very readily available to the plant, while the organic forms must pass through the various biological processes before the plant can use the nitrogen so contained. Only the best-known fertilizer carriers need receive particular attention here.

244. Dried blood and tankage.[1]—Both of these fertilizers are packing-house products. The former is obtained by drying the blood from the slaughtering pens. It comes on the market as a homogeneous blackish to dark greyish material, often slightly moist and with a characteristic odor. Its content of ammonia (NH_3) ranges from 10 to 16 per cent., depending on the grade of the fertilizer. It often contains traces of phosphoric acid (P_2O_5).[2]

Tankage is a mixture of various refuse materials from the slaughter-houses, such as blood, hair, scraps of meat, and hide and bone. It is generally steam-cooked and part of the gelatin and fat removed. It is variable in composition, carrying from 5 to 10 per cent. of NH_3 and from 3 to 8 per cent. of P_2O_5. The phosphoric acid is contained in the bone and is in the form of tricalcium phosphate [$Ca_3(PO_4)_2$]. Tankage is easily distinguished from blood meal by its heterogeneous character.

When added to a soil, both blood and tankage undergo rapid decomposition, ammonification, and finally nitrification. Such fertilizers are, therefore, very effective in the late spring and summer. For early application, however, a material such as sodium nitrate is much better, since a biological transformation is unnecessary in order that it may be immediately utilized by the plants.

245. Other organic nitrogenous fertilizers.—Below will be found the composition of a number of other organic materials that have been or are still used as fertilizers. Only two need explanation. Guano consists of the excrement and carcasses of sea fowls, the composition depending on the climate and position in which it is found. Guano from an arid region contains ammonia, phosphoric acid, and potash. Under humid conditions only the phosphoric acid remains in any

[1] Fry, W. H., *Identification of Commercial Fertilizer Materials;* U. S. Dept. Agr., Bul. 97, 1914.

[2] The composition of commercial fertilizers is commonly expressed in terms of ammonia (NH_3), phosphoric acid (P_2O_5), and potash (K_2O).

amount. Typical guano carries uric acid, urates, and ammonium salts. The phosphorus occurs as calcium, potassium, and ammonium phosphates. The potash is found in the chloride, sulfate and phosphate forms. While guano was once a very important fertilizer, the deposits are very nearly exhausted and but little now appears on the market.

Process fertilizers are obtained by treating organic trade wastes and refuse with acid or with steam under pressure. Hydrolysis of the proteins occurs with the formation of proteoses, peptones, and simple amino acids. The water soluble nitrogen of such materials has been shown by Lathrop of the United States Bureau of Soils to be as readily available as that of dried blood or tankage.

TABLE XCV

FERTILIZER	NH_3	P_2O_5	K_2O
Guano	10–14	6– 7	2–5
Process goods	1– 3	——	——
Hoof meal	10–13	10–12	——
Fish scrap	8–11	6– 7	——
Leather meal	8–12	——	——
Wool and hair waste	10–16	——	——
Cottonseed meal	8–10	1– 2	2–3
Linseed meal	4– 6	1– 2	1–2
Castor pomace	5– 7	1– 1½	1–1½

These compounds vary greatly in their values as fertilizers. Guano, process goods, and fish scrap when in the soil decompose rapidly and are as effective ordinarily as blood or tankage. Untreated leather meal and wool and hair waste decay very slowly and are of little value as fertilizing materials.

246. Utilization of nitrogenous organic compounds by plants.—One of the early beliefs in regard to plant nutrition was that organic matter as such is directly absorbed by higher plants. This opinion was afterwards entirely replaced by the

mineral theory propounded by Liebig; and still later the discovery of the nitrifying process almost disposed completely of the belief that organic matter is used directly by higher plants. It is quite certain, however, that some organic nitrogenous compounds furnished suitable material for some higher plants without undergoing bacterial change and producing a nitrate form of nitrogen.

The following compounds have been shown by Hutchinson and Miller [1] to be readily assimilated by peas: acetamide, urea, barbituric acid, and alloxan. Formamide, glycerine, cyanuric acid, oxamine, peptone, and sodium aspartate were assimilated but less easily. Creatinine has been shown by Skinner [2] to be used directly by plants as a source of nitrogen. Histidine, arginine, and creatine have also been found in soils and it has been demonstrated that they have a direct influence on wheat seedlings.

These and numerous other investigations of this subject show that amine as well as amide nitrogen is assimilated by at least some agricultural plants, but to what extent most of these compounds may successfully replace the inorganic forms of nitrogen, such as the nitrates, has not been definitely established. Certain organic nitrogenous fertilizers—as, for example, dried blood—have a high commercial value, the nitrogen in this form selling for more a pound than the nitrogen in any of the inorganic salts. Many crops, especially certain vegetables, are most successfully grown only when supplied with organic nitrogenous material. Some nitrate nitrogen is always present under natural soil conditions, so that crops are never limited to organic nitrogen alone; and it may be that the latter form of nitrogen is most useful when it supplements the nitrate form.

[1] Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Centrlb. f. Bakt., II, Band 30, Seite 513-547, 1911.

[2] Skinner, J. J., III. *Effects of Creatinine on Plant Growth;* U. S. Dept. Agr., Bur. Soils, Bul. 83, pp. 33-44, 1911.

247. Sodium nitrate ($NaNO_3$ +).[1]—Sodium nitrate is mined in Chile, occurring as a crude salt (caliche) in the semiarid regions along the coast. It is found near the surface under an over burden of varying thickness. The caliche contains, besides sodium nitrate, such salts as NaCl, K_2SO_4, Na_2SO_4, and $MgSO_4$ besides traces of Na_2CO_3, K_2CO_3, and boron. The refined salt, which is shipped to this country, carries from 2 to 3 per cent. of NaCl and KNO_3. Its ammonium content is generally rated at about 18 per cent.

The fertilizer appears on the market in clouded crystals of a yellowish cast, extremely soluble in water and quite deliquescent. The fertilizer is generally alkaline to litmus. In the soil it diffuses rapidly and is immediately available to plants. For this reason it is extremely valuable early in the spring before nitrification is active.

The long-continued use of sodium nitrate will tend to produce an alkaline residue of sodium carbonate in the soil.[2] This is due to the absorptive power of the soil for sodium and the ease with which the nitrate ions are lost in drainage. The plant, by using large amounts of nitrates, intensifies this selective absorption.

The origin of the caliche deposits is problematical. The theory has been advanced that the origin is due to the decomposition of great deposits of seaweed on an uplifted continental shelf. Another hypothesis would have the deposits originate from wind-carried guano dust. As rational a theory as any is proposed by Singewald and Miller,[3] who believe the nitrates were leached from the Andes Mountains and

[1] Fertilizer materials are never pure salts. The plus after the formula indicates the presence of impurities.

[2] Hall, A. D., *The Effect of the Long Continued Use of Sodium Nitrate on the Constitution of the Soil;* Trans. Chem. Soc. (London), Vol. 85, pp. 950-971, 1904. Also, Brown, B. E., *Concerning Some Effects of Long-Continued Use of Sodium Nitrate and Ammonium Sulfate on the Soil;* Ann. Rep. Pa. State Coll., 1908-1909, pp. 85-104.

[3] Singewald, J. N., and Miller, B. L., *Genesis of the Chilean Nitrate Deposits;* Econ. Geol., Vol. II, pp. 103-113, 1916.

carried by ground water to their present location. The concentration of the salts is considered by these authors as due to surface evaporation and consequent upward capillary movement of the highly charged ground water.

248. Ammonium sulfate ($(NH_4)_2SO_4$ +).—This fertilizer is a by-product from coke ovens and from the distillation of coal in gas manufacture.[1] About one-fifth of the nitrogen of the coal is thus driven off as ammonia, which is caught in special washing devices. The mother liquid is then distilled, the NH_3 being driven into sulfuric acid. The product is later concentrated and the salt crystallized out. Another and simpler process provides for a direct union of the gas and the acid, thus eliminating the washers.

This fertilizer usually carries about 25 per cent. of ammonia. It usually has a greyish or greenish color due to coal-tar products. This commercial ammonium sulfate is very soluble in water and has a characteristic taste. When heated, it readily breaks up, giving off ammonia gas. It is very acid to litmus paper, due to the union of a weak base with a strong acid radical. The ammonia is very strongly absorbed by the soil and also is used to a greater extent by the plant than are the sulfate ions. It thus leaves in the soil an acid residue[2] which should be alleviated by lime if the soil is not already supplied with plenty of active calcium and magnesium. In a warm soil the ammonia is quickly nitrified to the nitrate form. This transformation is general-

[1] *By-Product Coke and Gas Plants;* The Koppers Company, Pittsburgh.

Sulfate of Ammonia. Its Source, Production and Use; The Barrett Company, New York.

[2] Hall, A. D., and Gimingham, C. T., *The Interaction of Ammonium Salts and the Constitution of the Soil;* Jour. Chem. Soc. (London), Vol. 91, pt. 1, p. 677, 1907.

White, J. W., *The Results of Long Continued Use of Ammonium Sulfate Upon a Residual Limestone Soil of the Hagerstown Series;* Ann. Rep. Pa. State Coll., 1912-1913, pp. 55-104.

Ruprecht, R. W., and Morse, F. W., *The Effect of Sulfate of Ammonia on Soil;* Mass. Agr. Exp. Sta., Bul. 165, 1915.

ly so rapid as to make this fertilizer almost as quickly effective as sodium nitrate.

While the nitrogen of ammonium salts is quickly changed to the nitrate combination in a well-drained soil, some plants seem to prefer ammoniacal nitrogen to the nitrate form. Kellner [1] in 1884 and later Kelley [2] demonstrated that rice plants growing on lowland soils use ammoniacal nitrogen rather than other forms. On upland soils, however, it is presumable that rice plants utilize nitrate nitrogen, which would indicate that some plants, at least, may adapt themselves to the use of a more abundant form of nitrogen.

Hutchinson and Miller [3] found that peas obtained nitrogen from ammonium salts as readily as from sodium nitrate, but that wheat plants, although able to obtain nitrogen directly from ammonium salts, grew much better in a solution containing nitrates. One feature brought out by the numerous experiments with ammonium salts is the difference between plants of various kinds in respect to their ability to absorb nitrogen in this form.

249. The artificial fixation of nitrogen.[4]—The vast store of atmospheric nitrogen, chemically uncombined and very inert, will furnish an inexhaustible supply for plants when it can with reasonable economy be combined in some manner to give a product that can be commercially transported and that will, when placed in the soil, become available without liberating substances toxic to plants. The importance of the

[1] Kellner, O., *Agrikulturchemische Studien über die Reiskultur;* Landw. Vers. Stat., Band 30, Seite 18-41, 1884.

[2] Kelley, W. P., *The Assimilation of Nitrogen by Rice;* Haw. Agr. Exp. Sta., Bul. 24, pp. 5-20, 1911.

[3] Hutchinson, H. B., and Miller, N. H. J., *The Direct Assimilation of Inorganic and Organic Forms of Nitrogen by Higher Plants;* Centrlb. f. Bakt., II, Band 30, Seite 513-547, 1911.

[4] Norton, T. H., *Utilization of Atmospheric Nitrogen;* U. S. Dept. of Comm. and Labor, Special Agents Ser., No. 52, 1912.

Knox, J., *Fixation of Atmospheric Nitrogen;* New York.

Slosson, E. E., *Creative Chemistry,* Chaps. II and III; New York, 1920.

nitrogen supply for agriculture may be appreciated when it is considered that nitrates are being carried off in the drainage water of all cultivated lands at a surprisingly rapid rate. A Dunkirk silty clay loam at Cornell University,[1] carrying a rotation of maize, oats, wheat, and hay, lost in crop and drainage water in a period of ten years over 77 pounds to the acre of nitrogen annually. This is equivalent to 520 pounds of commercial sodium nitrate or to about 380 pounds of commercial ammonium sulfate.

The exhaustion of the supply of nitrogen in most soils may be accomplished within one or two generations, unless a renewal of the supply is brought about in some way. Natural processes provide for an annual accretion through the washing-down of ammonia and nitrates by rain-water from the atmosphere, and through the fixation of free atmospheric nitrogen by bacteria. Farm practice of the present day requires the application of nitrogen in some form of manure, and, as the end of the commercial supply of combined nitrogen is easily in sight, there is urgent need of discovering a new source. The world war has given great impetus to the study of the artificial fixation of nitrogen and a number of compounds thus produced are on the market or will appear shortly.

250. Calcium Cyanamid[2] ($CaCN_2$+).—The manufacture of this fertilizer begins with calcium carbide (CaC_2) which is produced by heating lime and coke together.

$$CaO + 3C = CaC_2 + CO$$

This impure carbide is then powdered and heated electrically in special ovens. At the proper temperature nitrogen gas is passed through the carbide with the following result:

$$CaC_2 + N_2 = CaCN_2 + C$$

[1] For complete data, see par. 163, this text.
[2] Pranke, E. J., *Cyanamid;* Easton, Pa., 1913.

The product is a black dry crystalline powder of rather light weight, containing about 20 per cent. of NH_3. It is very impure as shown by the following analysis:

$CaCN_2$	45.9	C	13.1
$CaCO_3$	4.0	Fe_2O_3 and Al_2O_3	1.9
CaS	1.7	SiO_2	1.6
Ca_3P_2	.1	MgO	.1
$Ca(OH)_2$	26.6	H_2O	.3

Its odor and the presence of carbon are characteristic. It is intensively alkaline to litmus. In the soil it undergoes a number of very complex changes, urea ultimately being produced. Toxic compounds are present as the reactions proceed. It should, therefore, be placed in the soil some time before the crop is seeded. The carbon seems to aid in the transformation as a catalytic agent. The urea quickly breaks down biologically to ammonia:

$$CON_2H_4 + 2H_2O = (NH_4)_2\ CO_3$$

This ammonia is then oxidized to the nitrate form.

251. Basic calcium nitrate ($Ca(NO_3)_2+$).—This fertilizer, like calcium cyanamid, is produced by the artificial fixation of nitrogen. Air is passed through an electric arc of high temperature. Under such conditions a part of the oxygen and the nitrogen are forced together forming nitric oxide. This gas is then oxidized in suitable chambers to the peroxide, which is passed into water, producing nitric acid. The nitric oxide which also results is led back to the oxidizing chambers.

The reactions are as follows:

$$N_2 + O_2 = 2NO$$
$$2NO + O_2 = 2NO_2$$
$$3NO_2 + H_2O = 2HNO_3 + NO$$

The nitric acid is passed into lime-water, giving calcium nitrate. This fertilizer contains from 13 to 16 per cent. of ammonia and is intensely alkaline to litmus. Due to its high

deliquescence, it must either be treated in some way, which raises the cost of manufacture, or must be shipped in sealed casks. It is very soluble in water and is immediately available to plants. It leaves no harmful residue in the soil.

252. Other methods of nitrogen fixation.—Calcium nitrate, because of its cost, cannot compete either with sodium nitrate or ammonium sulfate and is not manufactured in this country. Calcium cyanamid is produced only in amounts sufficient to satisfy the demands of mixed fertilizer manufacture. Its dry character makes it valuable in such compounding.

At the present time a number of more efficient methods of artificially fixing nitrogen are known. The Haber process proved extremely successful in Germany, especially when supplemented by the Oswald method of converting ammonia into nitric acid. In the Haber method a mixture of nitrogen and hydrogen are placed under pressure and moderately heated in the presence of a catalyst. A good yield of ammonia results.

$$N_2 + 3H_2 = 2NH_3$$

In the Oswald method this ammonia is passed over a catalytic agent in the presence of oxygen.

$$NH_3 + 2O_2 = HNO_3 + H_2O$$

The advantage of producing both ammonia and nitric acid is obvious, as ammonium nitrate (NH_4NO_3), ammonium phosphate ($(NH_4)_3PO_4$), and potassium nitrate (KNO_3) may be produced at one plant.

During the war Professor Bucher of Brown University perfected a simple and inexpensive method of producing sodium cyanide synthetically. Producers gas, formed by passing air over hot coal, is forced through a heated revolving drum containing soda ash, iron, and coke. The reaction is as follows:

$$Na_2CO_3 + 4C + N_2 = 2NaCN + 3CO$$

Ammonia may be produced very easily from the sodium cyanide and used as such or changed to nitric acid by the Oswald method.

253. Relative availability of nitrogen fertilizers.[1]—It is very difficult to rank nitrogenous fertilizers on the basis of their rate of availability, since the conditions within the soil so markedly influence the transformations, especially those of a biological nature. Dried blood and ammonium sulfate, for example, will give almost as quick results in a warm, well aërated soil, as far as higher plants are concerned, as sodium nitrate. In general, however, the nitrate fertilizers should be rated as most readily available, followed in order by ammonium salts, dried blood, tankage, and similar materials. Such substances as wool, hair, and untreated leather waste should rank last.

FERTILIZERS USED FOR THEIR PHOSPHORUS

Phosphorus is generally present in nature in combination with calcium, iron, or aluminum. Some phosphates carry organic matter and when thus associated are generally considered to decompose more readily when added to the soil.

254. Bone phosphate ($Ca_3(PO_4)_2+$).—Bones were formerly applied to the soil in the raw condition, either ground or unground. Most bone as now sold is merely steamed or boiled to remove the fat and nitrogenous matter, which is used in other ways. Bone-meal comes on the market as a dusty powder of characteristic odor. It contains about 27 per cent. of phosphoric acid as tricalcium phosphate. Tankage, which has already been spoken of as a nitrogenous fertilizer, contains from 3 to 8 per cent. of phosphoric acid, largely in the form of tricalcium phosphate. All bone phosphates are slow-acting manures, and should be used in a finely ground form and for the permanent benefit of the soil rather than as an

[1] Thorne, C. E., *Carriers of Nitrogen in Fertilizers;* Soil Sci., Vol. IX, No. 6, pp. 487-494, 1920.

immediate source of phosphorus. In the soil, water charged with carbon dioxide slowly converts the insoluble tricalcium phosphate into the soluble mono-calcium form:

$$Ca_3(PO_4)_2 + 4CO_2 + 4H_2O = CaH_4(PO_4)_2 + 2CaH_2(CO_3)_2$$

255. Rock phosphate[1] ($Ca_3(Po_4)_2+$).—There are many natural deposits of mineral phosphates in different parts of the world, some of the most important of which are in North America. The phosphorus in all of these is in the form of tricalcium phosphate, but the materials associated with it vary greatly. Rock phosphate may occur in nature as soft phosphate, pebble phosphate, boulder phosphate, and hard rock phosphate.

South Carolina phosphate contains from 26 to 28 per cent. of phosphoric acid and a very small amount of iron and aluminum. As these latter substances interfere with the manufacture of acid phosphate from rock, their presence is very undesirable, rock containing more than from 3 to 6 per cent. being unsuitable for that purpose.

Florida phosphates exist in the form of soft phosphate, pebble phosphate, and boulder phosphate. Such phosphate contains from 18 to 30 per cent. of phosphoric acid, and because of its being softer than most of these rocks it is often applied to the land without being first converted into a soluble form. The other two forms, pebble phosphate and boulder phosphate, are highly variable in composition, ranging from 20 to 40 per cent. in phosphoric acid content. Tennessee phosphate, which is now very important, contains from 25 to 35 per cent. of phosphoric acid.

Rock phosphate, or *floats* as it is often called, appears on the market as a heavy finely ground powder of light gray color. It generally carried about 27 per cent. of phosphoric acid as $Ca_3(PO_4)_2$. A typical analysis is as follows:

[1] Waggaman, W. H., and Fry, W. H., *Phosphate Rock and Methods Proposed for Its Utilization as a Fertilizer;* U. S. Dept. Agr., Bul. 312, 1915.

Moisture, organic matter, etc.	5.06
$Ca_3(PO_4)_2$	77.76
$FePO_4$ and $AlPO_4$	1.50
$CaCO_3$	4.43
$MgCO_3$	.50
$CaF_2 + CaCl_2$	6.11
FeS	.77
Fe_2O_3 and Al_2O_3	3.87

Rock phosphate undergoes the same change in the soil as bone-meal but generally much more slowly, unless the soil is very high in organic matter. Mixing the rock with manure seems to hasten its availability to plants.

256. Acid phosphate[1] ($CaH_4(PO_4)_2+$).—Acid phosphate is a dry material of a browning gray color, partially soluble in water, and has a characteristic acrid odor. It is intensely acid to litmus, as it contains certain acid salts. It carries from 14 to 16 per cent. of available P_2O_5 and small amounts of insoluble P_2O_5. It is made by treating raw rock with sulfuric acid under the proper conditions.[2]

$$\underset{\text{(insoluble)}}{Ca_3(PO_4)_2} + 2H_2SO_4 = \underset{\text{(water soluble)}}{CaH_4(PO_4)_2} + 2Ca\,SO_4$$

The acid is never added in amounts capable of quite completing this reaction. Some di-calcium phosphate [$Ca_2H_2(PO_4)_2$], spoken of as citrate soluble or reverted phosphoric acid, is thus produced.

$$\underset{\text{(insoluble)}}{Ca_3(PO_4)_2} + H_2SO_4 = \underset{\text{(reverted)}}{Ca_2H_2(PO_4)_2} + CaSO_4$$

Acid phosphate consists mostly of gypsum and mono-calcium phosphate with some di-calcium phosphate and impuri-

[1] Chemically, three forms of phosphoric acid are recognized by the fertilizer industry: (1) insoluble ($Ca_3(PO_4)_2$), (2) reverted or citrate soluble ($Ca_2H_2(PO_4)_2$), and (3) water soluble ($CaH_4(PO_4)_2$). The water soluble and citrate soluble phosphates are rated as *available* to plants. The insoluble form is considered as *unavailable*.

[2] Waggaman, W. H., *The Manufacture of Acid Phosphate;* U. S. Dept. Agr., Bul. 144, 1914.

ties. The water soluble and reverted phosphoric acid are both rated as available.

The phosphates of acid phosphate when added to the soil quickly revert to an insoluble form:

$$CaH_4(PO_4)_2 + 2CaH_2(CO_3)_2 = Ca_3(PO_4)_2 + 4CO_2 + 4H_2O$$
$$Ca_2H_2(PO_4)_2 + CaH_2(CO_3)_2 = Ca_3(PO_4)_2 + 2CO_2 + 2H_2O$$

Plenty of active calcium should be present when acid phosphate is used to insure this reaction instead of the formation of the very insoluble ferric phosphate ($FePO_4$) and aluminum phosphate ($AlPO_4$). Acid phosphate does not seem to make the soil acid.[1] In fact, it is considered by some investigators to decrease the acidity by rendering aluminum and iron insoluble.

257. Basic slag ($(CaO)_5.P_2O_5.SiO_2+$).—Iron or steel containing over 2 per cent. of phosphorus is too brittle to be useful and, as a consequence, ores of this character were little used until methods of removing this phosphoric acid were discovered. The use of wood in smelting provided a basic ash, thus removing phosphorus from the pig iron. With coal, however, the slag is acid and the phosphorus remains with the ore. In the open-hearth method of smelting the furnaces are lined with a specially prepared dolomitic limestone. Lime is later added as the smelting proceeds. The calcium of the slag unites with the phosphorus of the iron, thus reducing the percentage of that element in the steel. The most probable formula for the phosphorus compound in basic slag is $(CaO)_5.P_2O_5.SiO_2$. Basic slag contains a large amount of iron and calcium hydroxide. Below is a typical analysis:

CaO	45.0	Al_2O_3	1.7
MgO	6.2	SiO_2	6.9
$FeO + Fe_2O_3$	17.6	P_2O_5	18.1
MnO	3.5	Other constituents	1.0

[1] Conner, S. D., *Acid Soils and the Effect of Acid Phosphate and Other Fertilizers Upon Them;* Jour. Ind. and Eng. Chem., Vol. 8, No. 1, pp. 35-40, 1916.

Basic slag comes on the market as a heavy dark gray powder, extremely alkaline to litmus, and contains from 14 to 20 per cent. of P_2O_5. The phosphorus of basic slag is almost all soluble in citric acid and, therefore, is rated as available phosphoric acid. It does not revert in the soil as does acid phosphate, but is immediately attacked by carbon dioxide and rendered rather quickly available. A possible reaction is as below:

$$(CaO)_5.P_2O_5.SiO_2 + 8CO_2 + 6H_2O = CaH_4(PO_4)_2 + 4CaH_2(CO_3)_2 + SiO_2$$

258. Relative availability of phosphate fertilizers.—Acid phosphate carries most of its phosphoric acid in a water-soluble form and although the phosphates revert to the tricalcium form immediately when added to the soil, they are rather readily available to plants. This is due to the character of the freshly precipitated salt and the surface exposed for solution activities. To insure a good distribution in the soil of the phosphoric acid and a rapid influence on crops, acid phosphate should be well mixed with the soil.

Basic slag, since its phosphoric acid is largely citrate soluble, is generally considered as next to acid phosphate in availability. Steamed bone-meal usually gives better results than raw rock phosphate and rates third, with rock phosphate fourth in availability. The degree of fineness makes a great difference in the availability of the less soluble phosphate fertilizers, especially the ground bone and raw rock phosphate. The latter material should be ground fine enough to pass through a sieve having at least one hundred meshes to the inch.

259. Raw rock phosphate versus acid phosphate.—Considerable discussion as well as controversy has of late arisen regarding the relative merits of acid phosphate and raw rock phosphate not only when applied on the basis of equal amounts of phosphoric acid but also when compared on the basis of

equal money values. If rock phosphate could be made to equal or nearly equal the availability of acid phosphate, obvious advantages would accrue, since raw rock costs much less than acid phosphate and carries about twice as much phosphoric acid.

The availability of the phosphorus of raw rock phosphate varies considerably with conditions. At least four major influences have been recognized: (1) the character of the crop grown, (2) reaction of the soil, (3) the character of accompanying salts, and (4) the decomposition of organic matter. It is to be expected that the various kinds of plants should not be equally influenced by the phosphorus of tri-calcium phosphate. Prianischnikov [1] found that lupines, mustard, peas, buckwheat, and vetch responded to fertilization with raw rock phosphate in the order named, while the cereals did not respond at all. He did not include maize in his experiments, but that crop is said to respond well to difficultly soluble phosphates. It is generally considered that those plants which have a long growing season are better able to utilize tri-calcium phosphate than are more rapidly growing plants.

A number of investigators have stated, as a result of their experimentation, that the availability of raw rock phosphate is greater in acid soils than in those strongly basic. If acidity of the soil is due to the presence of an actual acid, it is conceivable that the availability may be due to the solvent action of the soil acid on the calcium of the tri-calcium phosphate, producing the di-calcium salt which appears to be fairly readily available to plants. When, however, soil acidity is due to a lack of certain active bases, the case is different. Gedroiz [2]

[1] Prianischnikov, D., *Bericht über Verschiedene Versuche mit Rohphosphaten unter Reduction;* Moscow, 1910.

[2] Gedroiz, K. K., *Soils to which Rock Phosphates May Be Applied with Advantage;* Jour. Exp. Agron. (Russian), Vol. 12, pp. 529-539, 811-816, 1911. The authors are indebted to Dr. J. Davidson for the translation.

explains this on the basis of the absorptive properties of the so-called acid soil. He regards rock phosphate, not as a chemical compound, but as a solid solution of di-calcium phosphate with lime. According to Gedroiz it is this excessive basicity of the phosphate which is responsible for its unavailability. Absorption of the excess calcium would leave the phosphate in a more readily available condition by forming the di-calcium salt.

The presence of certain salts has been found to influence the availability of difficultly soluble phosphates. The subject has been investigated by a large number of experimenters, and it will be possible to summarize their results only in part and very briefly. It has been found, for example, that calcium carbonate decreases the availability of raw rock phosphate and bone-meal. Sodium nitrate reduces the availability of the tri-calcium phosphates, while the ammonium salts increase their availability. Iron and aluminum salts decrease availability. The influence of other salts has not been so well worked out. Prianischnikov,[1] as the result of his extended experiments on the subject, holds that salts from which plants absorb acid radicals in larger amounts than they do bases decrease availability, or at least do not affect it, while salts from which plants absorb the bases in the greater quantity have a tendency to render the phosphate more available because of the hydrogen ion concentration.

There has been great differences of opinion among investigators as to the effect of the decomposition of organic matter on the availability of the phosphorus of tri-calcium phosphate. The contention that the availability is increased probably originated with Stoklasa,[1] whose experiments with bone-meal

[1] Prianischnikov, D., *Über den Einfluss von Kohlensäuren Kalk auf die Wirkung von Verschiedenen Phosphaten*; Landw. Vers. Stat., Band 75, Seite 357-376, 1911.

[2] Stoklasa, J., Duchacek, F., and Pitra, J., *Über den Einfluss der Bakterien auf die Knochenzersetzung;* Centrlb. f. Bakt., II, Band 6, Seite 526-535, 554-558, 1900.

indicate that the availability is increased by decay. A large number of experiments have been conducted with raw rock phosphate composted with stable manure, among which may be mentioned those by Hartwell and Pember [1] and also by Tottingham and Hoffman,[2] who, in carefully conducted experiments, failed to find that the availability of the raw phosphate, as indicated by chemical methods, was increased by fermentation with stable manure. Opposing results have also been obtained, however, and the evidence is somewhat conflicting.

With so many factors active in varying the results, especially those from raw rock phosphate, it is not surprising that satisfactory field data where acid phosphate and raw rock are compared are difficult to obtain. Thorne,[3] after a critical review of the field experiments where acid phosphate and raw rock were used, comes to the conclusion that, while raw rock phosphate is an excellent fertilizer, acid phosphate is generally superior. He finds that, while raw rock may be used with profit on land materially deficient in phosphorus, acid phosphate has generally proven to be the more effective and the more economical carrier of phosphoric acid for crops.

These conclusions, which are corroborated by other investigators,[4] do not imply that raw rock phosphate is never equal or superior to acid phosphate, nor that raw rock does not have a place as a fertilizer on the average farm. On a

[1] Hartwell, B. L., and Pember, F. R., *The Effect of Cow Dung on the Availability of Rock Phosphate;* R. I. Agr. Exp. Sta., Bul. 151, 1912.

[2] Tottingham, W. E., and Hoffman, C., *The Nature of the Changes in Solubility and Availability of Phosphorus in Fermenting Mixtures;* Wis. Agr. Exp. Sta., Res. Bul. 29, 1913.

[3] Thorne, C. E., *Raw Phosphate Rock as a Fertilizer;* Ohio Agr. Exp. Sta., Bul. 305, 1916.

[4] Wiancko, A. T., and Conner, S. D., *Acid Phosphate versus Raw Rock Phosphate as Fertilizer;* Purdue Univ. Agr. Exp. Sta., Bull. 187, 1916.

Brooks, W. P., *Phosphates in Massachusetts Agriculture;* Mass. Agr. Exp. Sta., Bull. 162, 1915.

Waggaman, W. H., and Wagner, C. R., *Analysis of Experimental Work with Ground Raw Rock Phosphate as a Fertilizer;* U. S. Dept. Agr., Bul. 699, 1918.

soil rich in organic matter it may be added to advantage. It is especially useful in reinforcing farm manure, seemingly being about as effective under such conditions as is acid phosphate. Its higher phosphorus content and lower cost a ton gives it an added advantage. The figures from Ohio,[1] covering a period of fourteen years in a rotation of maize, wheat, and hay may be taken as evidence regarding these points. The manure, reinforced to the ton with 40 pounds of acid phosphate and raw rock phosphate, respectively, was applied to the corn at the rate of eight tons to the acre.

TABLE XCVI

A COMPARISON OF ACID PHOSPHATE AND RAW ROCK IN EQUAL WEIGHTS WHEN ADDED TO THE SOIL WITH MANURE.

MANURE	AVERAGE ANNUAL INCREASE TO THE ACRE		
	MAIZE 14 CROPS	WHEAT 14 CROPS	HAY 11 CROPS
With raw rock.....	25.0 bu.	12.9 bu.	1578 lbs.
With acid phosphate.....	30.6 bu.	15.1 bu.	1853 lbs.

FERTILIZERS USED FOR THEIR POTASSIUM

The production of potassium fertilizers is largely confined to Germany, where there are extensive beds varying from 50 to 150 feet in thickness, lying under an area extending from the Harz Mountains to the Elbe River and known as the Stassfurt deposits. Large deposits of crude potash salts occur in other sections of Germany, and also in France. While small deposits occur in other parts of the world the French and German mines are at present the only ones of any great commercial importance. The World War stimulated considerable investigation regarding possible sources of

[1] Thorne, C. E., *et al., Plans and Summary Tables of the Experiments at the Central Farm;* Ohio. Agr. Exp. Sta., Circ. 120, p. 112, 1912.

potash, especially in the United States. Kelp, saline brines, deposits in old lake beds, and flue dust yielded considerable potassium. Most of these sources, however, are too expensive to compete with European potash in normal times.

260. Stassfurt salts and their refined equivalents.—The Stassfurt salts contain their potassium either as a chloride or as a sulfate. The chloride has the advantage of being more diffusible in the soil, but in most respects the sulfate is preferable. Potassium chloride in large applications has an injurious effect on certain crops, among which are tobacco, sugar-beets, and potatoes. On cereals, legumes, and grasses the muriate appears to have no injurious effect.

Kainit is the most common of the crude products of the Stassfurt mines and is imported into this country in large amounts. It is generally a greyish vari-colored salt, soluble in water and alkaline to litmus. It carries from 12 to 14 per cent. of K_2O, largely as potassium sulfate. Its potash is immediately available to the crop. Below is a typical analysis:

K_2SO_4	21.3	NaCl	34.6
KCl	2.0	$CaSO_4$	1.7
$MgSO_4$	14.5	Insoluble	.8
$MgCl_2$	12.4	H_2O	12.7

Silvinit contains its potassium both as a chloride and as a sulfate. It also contains sodium and magnesium chlorides. Potash constitutes about 16 per cent. of the material. Owing to the presence of chlorides, it has the same effect on plants as has kainit. There are a number of other Stassfurt salts, consisting of mixtures of potassium, sodium, and magnesium in the form of chlorides and sulfates. They are not so widely used for fertilizers as are those mentioned above.

A great proportion of the crude salts are refined for export purposes, appearing on the market as either the chloride or the sulfate. They usually contain from 48 to 50 per cent.

of potash. The chief impurity is common salt. Some of the potash salts produced in this country carry boron, which is extremely toxic to plants. Such is not generally true of the German and French products.

Potassium chloride and potassium sulfate when added to the soil are immediately soluble, being held in the soil solution or absorbed either physically or chemically by the colloidal complexes. Due to the selective absorption of the soil for the potassium ion and the fact that plants absorb more of this ion than of the acid radical, an acid residue tends to result from the use of such fertilizers. Some means, such as the use of lime, should be employed to counteract this tendency.

261. Other sources of potash.[1]—For some time after the use of fertilizers became an important farm practice, wood-ashes were the source of most of the potash. They also contain a considerable quantity of lime and a small amount of phosphorus. The product known as unleached wood-ashes contains from 5 to 6 per cent. of potash, 2 per cent. of phosphoric acid, and 30 per cent. of calcium oxide. Leached wood-ashes contain about 1 per cent. of potash, 1½ per cent. of phosphoric acid, and from 28 to 29 per cent. of lime in the form of the hydroxide and carbonate. Unleached ashes carry the oxide, hydroxide, and carbonate forms of calcium. Ashes contain the potassium in the form of a carbonate, (K_2CO_3), which is alkaline in its reaction and in large amounts may be injurious to seeds. Otherwise this form of potash is very desirable, since no acid residue is left in the soil by its use.

[1] Young, G. J., *Potash Salts and Other Salines in the Great Basin;* U. S. Dept. Agr., Bul. 61, 1914.

Waggaman, W. H., and Cullen, J. A., *The Recovery of Potash from Alunite;* U. S. Dept. Agr., Bul. 415, 1916.

Hirst, C. T., and Carter, E. G., *Some Sources of Potassium;* Utah Agr. Exp. Sta., Circ. 22, 1916.

Waggaman, W. H., *The Production and Fertilizer Value of Citric-Soluble Phosphoric Acid and Potash;* U. S. Dept. Agr., Bul. 143, 1914.

Ross, W. H., *et al., The Recovery of Potash as a By-Product in the Cement Industry;* U. S. Dept. Agr., Bul. 572, 1917.

Ashes are beneficial to acid soils through the action of both the potassium and calcium salts.

Insoluble forms of potassium, existing in many rocks usually in the form of a silicate, are not regarded as having any manurial value. Experiments with finely ground feldspar have been conducted by a number of investigators, but have, in the main, offered little encouragement for the successful use of this material. Leucite and alunite have given but little better results. An insoluble form of potassium is not recognized as of value when a fertilizer is rated on the basis of chemical analysis.

During the World War, since the German importation of potash salts ceased, potassium was sought commercially from a number of sources in this country. Alunite, a hydrous sulfate of aluminum and potassium, has been experimented with to some extent as have also the green-sand marls which carry glauconite. In a number of cases the recovery of potash from flue dust has proven commercially profitable. It is estimated that 87,000 tons of potash are lost yearly from cement kilns alone in the United States and Canada. During the war considerable progress was made in harvesting and drying the kelp which grows off the coast of southern California. The kelp was later extracted for its potash. This source of potassium is rather expensive, however, when brought into competition with European products.

Perhaps the most reliable sources of domestic potash are the brines of certain alkali lakes of western United States and from the deposits in old lake beds in the same region.[1] The exploitation of such sources will, of course, depend upon the price at which German potash can be laid down in this country.

[1] Such salts unless properly prepared are likely to contain borax which is usually toxic when applied at a greater rate than five pounds to the acre, the influence being more intense at low soil moisture.

Neller, J. R., and Morse, W. J., *Effects upon the Growth of Potatoes, Corn and Beans, Resulting from the Addition of Borax to the Fertilizer used;* Soil Sci., Vol. XII, No. 2, pp. 79-105, 1921.

SULFUR AND SULFATES AS FERTILIZERS [1]

The use of these substances as a means of increasing plant growth when applied to soils has recently received much attention. While sulfates have been used for centuries as a soil amendment, it is only within the last few years that sulfur itself has been applied to soil. The question of the effect of the latter has received considerable study, not only in France and Germany but in this country as well. The influence of both sulfur and sulfates may be a direct nutrient relationship or the action may be that of a soil amendment. Only in case the former influence occurs could these materials be rated as fertilizers.

262. The use of free sulfur.—Boullanger [2] in 1912 added

[1] Another group of fertilizers may be mentioned—the so-called *catalytic fertilizers.* Such materials are supposed to aid plant growth by accelerating natural soil processes. The catalytic action of any material is very difficult to establish when it is added to the soil, since the soil itself carries many substances of a catalytic nature. Manganese has been most seriously considered as a catalytic fertilizer.

König, J., Hasenbäumer, J., and Coppenrath, E., *Einige Neue Eigensehaften des Aekerbodens;* Landw. Vers. Stat., Band 63, Seite 471-478, 1905-1906.

May, D. W., and Gile, P. L., *The Catalase of Soils;* Porto Rico Agr. Exp. Sta., Circ. 9, 1909.

Sullivan, M. X., and Reid, F. R., *Studies in Soil Catalysis;* U. S. Dept. Agr., Bur. Soils, Bul. 86, 1912.

König, J., Hasenbäumer, J., and Coppenrath, E., *Beziehungen zwisehen den Eigensehaften des Bodens und der Nährstoffaufnahme durch die pflanzen;* Landw. Vers. Stat., Band 66, Seite 401-461, 1907.

Kelly, M. P., *The Influenec of Manganese on the Growth of Pineapples;* Jour. Ind. and Eng. Chem., Vol. I, p. 533, 1909.

Sullivan, M. X., and Robinson, W. O., *Manganese as a Fertilizer;* U. S. Dept. Agr., Bur. Soils, Circ. 75, 1912.

Skinner, J. J., and Sullivan, M. X., *The Aetion of Manganese in Soils;* U. S. Dept. Agr., Bul. 42, 1914.

Skinner, J. J., and Reid, F. R., *The Aetion of Manganese Under Acid and Neutral Soil Conditions;* U. S. Dept. Agr., Bul. 441, 1916.

Bertrand, G., *The Action of Chemical Infinitesimals in Agriculture;* Address before 8th Inter. Cong. App. Chem., New York, 1912.

Ross, W. H., *The Use of Radioaetive Substanees as Fertilizers;* U. S. Dept. Agr., Bul. 149, 1914.

Hopkins, C. G., and Sachs, W. H., *Radium as a Fertilizer;* Ill. Agr. Exp. Sta., Bul. 177, 1915.

[2] Boullanger, E., *Action du soufre en fleur sur la végétation;* Compt. Rend. Acad. Sci. Paris, T. 154, pp. 369-370, 1912.

flowers of sulfur to a soil at the rate of 23 parts per million of soil. He obtained increased growth in all treated soils on which carrots, beans, celery, lettuce, sorrel, chicory, potatoes, onions, and spinach were grown, the weights of the crops on the treated soil being from 10 to 40 per cent. greater than those on the untreated soil. On soils that had been sterilized before applying sulfur, the effect was less marked, from which he concludes that the beneficial effects were due to the influence of the sulfur on the micro-organisms of the soil. There may be some question, however, whether this conclusion is justifiable. Sulfur was found by Boullanger and Dugardin [1] to favor ammonification in soils. Beneficial effects from the use of free sulfur have also been obtained by Demelon,[2] and by Bernhard,[3] while von Feilitzen [4] found it to be ineffective as a fertilizer.

In this country, Shedd [5] of Kentucky obtained increases in tobacco yield with sulfur. Perhaps the most marked results with sulfur are reported by Reimer and Tartar [6] from Oregon. Alfalfa and clover yields were increased from 50 to 100 per cent.

That free sulfur may, under certain conditions, exert a beneficial influence on plant growth must be conceded, but that the action is a direct nutritive one remains to be proven. Free sulfur is insoluble and cannot be absorbed as such by plants. It readily undergoes oxidation, however, producing the sulfate, as already explained under sulfofication. As such

[1] Boullanger, E., and Dugardin, M., *Mecanisme de l'action fertilisante du soufre;* Compt. Rend. Acad. Sci. Paris, T. 155, pp. 327-329, 1912.

[2] Demelon, A., *Sur l'action fertilisante du soufre;* Compt. Rend. Acad. Sci. Paris, T. 154, pp. 524-526, 1912.

[3] Bernhard, A., *Versuche über dis Wirkung des Schwefels als Dung im Jahre 1911;* Deutsche Landw. Presse., Band 39, S. 275, 1912.

[4] von Feilitzen, H., *Über die Verwendung der Schwefelblute zur Bekampfung des Kartoffelschorfes und als indirktes Dungemittel;* Fuhling's Landw. Zeit., Band 62, Seite 7, 1913.

[5] Shedd, O. M., *The Relation of Sulfur to Soil Fertility;* Ky. Agr. Exp. Sta., Bul. 188, 1914.

[6] Reimer, F. C., and Tartar, H. V., *Sulfur as a Fertilizer for Alfalfa in Southern Oregon;* Ore. Agr. Exp. Sta.. Bul. 163, 1919.

a reaction tends to encourage soil acidity, injurious influences may easily occur on soils already acid or possessing only small quantities of active calcium and magnesium. If sulfur functions as a fertilizer, it is by a change to the sulfate, in which form it is absorbed by plants.

263. The use of sulfate sulfur.—The experimental evidence regarding the direct fertilizer influence of sulfate sulfur is much more difficult to interpret than that regarding flowers of sulfur. Gypsum has been applied to soils for centuries and marked influences on crop growth are of common observation. Whether this stimulation is due to the sulfate or to the base which accompanies it cannot be determined. Even if the sulfate influence could definitely be proved, there would still remain the question as to whether the action was direct or indirect.

264. Relation of sulfur to soil fertility.—The possible deficiency of sulfur in arable soils was first established by Hart and Peterson.[1] They point out that crops remove more

TABLE XCVII

POUNDS SULFUR TRIOXIDE AND PHOSPHORUS PENTOXIDE REMOVED TO THE ACRE BY AVERAGE CROPS.

Crop and Yield to the Acre	Pounds to the Acre	
	SO_3	P_2O_5
Wheat (30 bu.)	15.7	21.1
Barley (40 bu.)	14.3	20.7
Oats (45 bu.)	19.7	19.7
Corn (30 bu.)	12.0	18.0
Alfalfa (9000 lbs. air dry)	64.8	39.9
Turnips (4657 lbs. air dry)	92.2	33.1
Cabbage (4800 lbs. air dry)	98.0	61.0
Potatoes (3360 lbs. air dry)	11.5	21.5
Meadow hay (2822 lbs. air dry)	11.3	12.3

[1] Hart, E. B., and Peterson, W. H., *Sulfur Requirements of Farm Crops in Relation to the Soil and Air Supply;* Wis. Agr. Exp. Sta., Res. Bul. 14, 1911.

sulfur from the soil than is indicated by the earlier analyses of plant ash, since considerable sulfur was lost by volatization in the former determination. On the basis of their own methods, they present the data given as to the removal of sulfur trioxide and phosphoric acid from the soil by average crops. (See Table XCVII, page 468.)

It is to be noted that the amount of sulfur removed by crops is generally about equal to and in some cases much in excess of the phosphoric acid taken from the soil. The fact that soils are generally as low in sulfur as in phosphoric acid lends weight to the argument, that if the latter is a limiting factor in productivity the former should be also.

To ascertain whether the supply of sulfur in the soil is really depleted by cropping, Hart and Peterson made parallel determinations of sulfur in five virgin soils and in five soils of the same respective types that had been cropped for sixty years. In each type the cropped soil contained less sulfur than the virgin soil, the average for the former being .053 per cent. SO_3 and for the latter .085 per cent. SO_3.

Considerable sulfur is added to the soil every year in the rain-water, largely in the sulfate form, although near cities appreciable amounts of hydrogen sulfide and sulfur di-oxide are formed. The amount of such sulfur is variable. Miller,[1] at the Rothamsted Experiment Station, reports 17.4 pounds of SO_3 to the acre, while Crowther and Ruston [2] near Leeds, England, found 161 pounds of SO_3 to the acre. Peck [3] found the addition of SO_3 to be at the rate of 1 pound to the acre a month at Mt. Vernon, Iowa, while Trieschmann,[4] over a

[1] Miller, N. H. J., *The Amount of Nitrogen, as Ammonia and as Nitric Acid, and of Chlorine in the Rain-Water Collected at Rothamsted;* Jour. Agr. Sci., Vol. I, pp. 280-303, 1905.

[2] Crowther, C., and Ruston, A. C., *The Nature, Distribution and Effect Upon Vegetation of Atmospheric Impurities In and Near an Industrial Town;* Jour. Agr. Sci., Vol. 4, pp. 25-55, 1911.

[3] Peck, E. L., *Nitrogen, Chlorine and Sulfates in Rain and Snow;* Chem. News., Vol. 116, p. 283, 1917.

[4] Trieschmann, J. E., *Nitrogen and other Compounds in Rain and Snow;* Chem. News, Vol. 119, p. 49, 1919.

different period at the same place, determined the addition to be less than .2 pound a month. Stewart,[1] at the University of Illinois, reports the addition of sulfur as SO_3 over a period of seven years as amounting to 9.4 pounds of SO_3 monthly to the acre or 113 pounds yearly.

The loss of sulfur expressed as SO_3 from the Cornell lysimeters,[2] due to cropping and drainage combined, amounted, over a period of ten years, to 149.5 pounds from an acre yearly from the rotation tanks. The addition of sulfur in the rain-water at Ithaca amounts to about 65.4 pounds of SO_3 each year. It is, therefore, safe to assume that rain-water will not replace the sulfur removed by normal cropping and leaching. It must be remembered, however, that in rational soil management, sulfur is returned to the soil in green-manures, crop residues and farm manures. Commercial fertilizers are now very commonly used, especially acid phosphate, which is about one-half gypsum. At the Ohio Experiment Station,[3] plats treated with sulfate bearing fertilizers were found over a period of years to contain considerably more sulfur than soils not so fertilized but cropped in a similar manner.

In the light of such data it seems that the sulfur problem is not comparable with or as serious as the phosphorus problem of soil fertility. By the careful utilization of the normal residues produced on the farm there seems little reason for sulfur being a limiting factor in soil productivity, especially if fertilizers carrying sulfur are used in connection with a rational system of soil management.

[1] Stewart, R., *Sulfur in Relation to Soil Fertility;* Ill. Agr. Exp. Sta., Bul. 227, 1920.

[2] Complete data on these lysimeters will be found in par. 163 of this text.

[3] Ames, J. W., and Boltz, G. E., *Sulfur in Relation to Soils and Crops;* Ohio Agr. Exp. Sta., Bul. 292, 1916.

CHAPTER XXIII

THE PRINCIPLES OF FERTILIZER PRACTICE [1]

THE USE of commercial fertilizers has increased so rapidly within the last decade that specific knowledge is needed regarding the various materials offered for sale in order that the most economical results may be attained. The greater the general knowledge, both practical and theoretical, that a person possesses as to the effects of the different nutrient constituents on plant growth, the more rational will be the fertilizer use. Fertilizer inspection and control, principles of buying and home-mixing, methods of application, mixtures for special crops, are a few of the many phases of economical fertilizer practice. The final and vital consideration is regarding the financial return from fertilizer application. A fertilizer should always pay.

As all fertilizers exert, either directly or indirectly, a residual effect, the problem necessarily broadens into a study of the systems of applying them to a series of crops or to a rotation, rather than a study of the effects of one particular fertilizer application on one particular crop.

265. Influence of nitrogen on plant growth.[2]—Of the three elements carried in an ordinary complete fertilizer,

[1] Hall, A. D., *Fertilizers and Manures;* New York, 1921.
Halligan, J. E., *Soil Fertility and Fertilizers;* Easton, Pa., 1912.
Van Slyke, L. L., *Fertilizers and Crops;* New York, 1912.
Fraps, G. S., *Principles of Agricultural Chemistry;* Easton, Pa., 1913.

[2] Discussions of the effects of the various elements on plants may be found as follows: Russell, E. J., *Soil Conditions and Plant Growth,* Chapter II, pp. 19-50; London, 1912. Also, Hall, A. D., *Fertilizers and Manures,* Chapters III, IV and VI; New York, 1921.

nitrogen [1] seems to have the quickest and most pronounced effect, not only when present in excess of other constituents, but also when moderately used. It tends primarily to encourage above ground vegetative growth and to impart to the leaves a deep green color, a lack of which is usually due to insufficient nitrogen. It tends in cereals to increase the plumpness of the grain, and with all plants it is a regulator in that it governs to a certain extent the utilization of potash and phosphoric acid. Its application tends to produce succulence, a quality particularly desirable in certain crops. In its general effects it is very similar to moisture, especially when supplied in excessive quantities.

The peculiarity of nitrogen lies not only in its absolute necessity for plant growth, its stimulation of the vegetative parts, and its close relationship to the general tone and vigor of the crop, but also in the fact that it was not one of the original elements of the earth's crust. During the formation of the soil it slowly and gradually became present, brought down by rains and fixed naturally in the soil through the agency of bacterial action. Now it exists in complex nitrogenous compounds of the more or less decayed organic matter, and becomes available to plants largely through bacterial activity.

It may be stated with certainty that one of the possible limiting factors to crop growth is a lack of water-soluble nitrogen at critical periods in amounts necessary for normal development. Since soluble nitrogen may be very readily lost from the soil by leaching, the problem of proper plant nutrition becomes a serious one. Not only must the farmer be able so to regulate the addition of nitrogen in fertilizers as to obtain the highest efficiency, but he must understand the control and

[1] For a discussion of nitrogen in relation to crop yield, see Hunt, T. F., *The Importance of Nitrogen in the Growth of Plants;* Cornell Agr. Exp. Sta., Bul. 247, 1907.

encouragement of the natural fixation as well. Due to the practical possibility of keeping up the nitrogen supply of the soil by the proper use of farm manure, crop residues, green-manures, and the utilization of legumes in the rotation, the quantity of nitrogen purchased in commercial fertilizers should be as small as possible if its use is to be profitable. When so purchased it should function more or less as a crop starter rather than as a source of any large amount of the plants' supply of nutrient. The emphasis placed on all phases of the nitrogen problem serves to reveal its great importance in fertility practices.

Because of the immediately visible effect from the application of soluble nitrogen, the average farmer is prone to ascribe too much importance to its influence in proper crop development. This attitude is unfortunate, since nitrogen is the highest priced constituent of ordinary fertilizers and should usually be purchased to a less extent than potash and especially than phosphoric acid. Moreover, of the three common fertilizer elements, it is the only one which, added in excess, will result in harmful after-effects on the crop. These possible and important detrimental effects of nitrogen may be listed as follows:

1. *It may delay maturity* by encouraging vegetative growth. This oftentimes endangers the crop to frost, or may cause trees to winter badly.

2. *It may weaken the straw and cause lodging in grain.* This is due to an extreme lengthening of the internodes, and as the head fills the stem is no longer able to support the increased weight.

3. *It may lower quality.* This is especially noticeable in certain grains and fruits, as barley and peaches. The shipping qualities of fruits and vegetables are also impaired.

4. *It may decrease resistance to disease.* This is probably due to a change in the physiological resistance within the

plant, and also to a thinning of the cell-wall, allowing a more ready infection from without.

While certain plants, as the grasses, lettuce, radishes, and the like, depend for their usefulness on plenty of nitrogen, it is generally better to limit the amount of nitrogen for the average crop so that growth may be normal. This results in a better utilization of the nitrogen and in a marked reduction of the fertilizer cost for a unit of crop growth. This is a vital factor in all fertilizer practice, and shows immediately whether nitrogen fertilization is or is not an economic success.

266. Influence of phosphorus on plant growth.—It is difficult to determine exactly the functions of phosphoric acid in the economy of even the simplest plants. Neither cell division nor the formation of fat and albumen go on to a sufficient extent without it. Starch may be produced when it is lacking, but will not change to sugar. As grain does not form without its presence, it very probably is concerned in the production of nucleoproteid materials. Its close relationship to cell division may account for its presence in seeds in comparatively large amounts.

Phosphoric acid hastens the maturity of the crop by its ripening influences. This effect is especially valuable in wet years and in cold climates where the season is short. The use of acid phosphate is being advocated in the Middle West, especially for maize, as an insurance against frost-injury and a means of avoiding soft corn. Phosphoric acid also encourages root development, especially of lateral and fibrous rootlets. This renders it valuable in such soils as do not encourage root extension and to such crops as naturally have a restricted root development. Phosphoric acid is especially valuable for fall-sown crops, such as wheat. A sturdy root growth is developed which tends to prevent winter injury and prepares the plant for a rapid spring development.

Phosphoric acid decreases the ratio of straw to grain in cereals. It also strengthens the straw, thus decreasing the

tendency to lodge, which is likely to occur especially with oats if too much available nitrogen is present. In certain cases, phosphoric acid decidedly improves the quality of the crop. This has been recognized in the handling of pastures in England and France. The effect on vegetables is also marked. Phosphorus is also known to increase the resistance of some plants to disease, due possibly to a more normal cell development. In this respect phosphoric acid counteracts the influence of a heavy nitrogen ration.

Excessive quantities of phosphoric acid ordinarily have no bad effect, as phosphorus does not stimulate any part unduly, nor does it lead to a development which is detrimental. The lack of phosphoric acid is not apparent in the color of the plants as in the case of nitrogen, and as a consequence phosphoric acid starvation may occur without any suspicion thereof being entertained by the farmer.

One of the most important phases to be noted from this comparison of the effects of nitrogen and phosphorus is the balancing powers of the latter on the unfavorable influences generated by the presence of an undue quantity of the former. The possible detrimental effects of too much nitrogen have already been noted. This relationship between the phosphorus and nitrogen in plant nutrition is very important in fertilizer practice, since normal fertilizer stimulation generally results in the most economical gains.

267. Effects of potassium on plant growth.—The presence of plenty of available potash in the soil has much to do with the general tone and vigor of the plant. By increasing resistance to certain diseases it tends to counteract the ill effects of too much nitrogen, while in delaying maturity it works against the ripening influences of phosphoric acid. In a general way, it exerts a balancing effect on both nitrogen and phosphate fertilizer materials, and consequently is especially important in a mixed fertilizer, if the potash of the soil is lacking or unavailable.

Potash is essential to starch formation, either in photosynthesis or in translocation, and is necessary in the development of chlorophyll. It is important to cereals in grain formation, giving plump heavy kernels. As with phosphorus, it may be present in large quantities in the soil and yet exert no harmful effect on the crop. While potassium and sodium are similar in a chemical way, sodium cannot take the place of potash in plant nutrition. Where there is an insufficiency of potash, however, sodium seems in some way, either directly or indirectly, to be useful.[1]

268. The element in the "minimum."—In connection with the obvious importance of utilizing, for any particular soil and crop, a fertilizer well balanced as to the three primary elements, two queries naturally arise. These are: (1) What are the proper proportions of nitrogen, phosphoric acid, and potash to apply under given conditions? (2) What would be the effect if any one of these should not be present in sufficient quantity as to make it equal in function to the others?

The first query cannot be disposed of until the question of fertilizer mixtures has been considered. The second, however, is not affected by so many factors, and is more clearly a question of the function of the elements concerned and is logically discussed at this point.

Any element that exists in relatively small amounts as compared with the other important nutrient constituents naturally becomes the controlling factor in plant development. Any reduction or increase in this element will cause a corresponding reduction or increase in the crop yield. This element, then, is said to be "in the minimum." In fertilizer practice, ideal conditions would exist if no constituent functioned as a decided minimum and the entire influence of each single element was fully utilized. In other words, the fertilizer would be balanced as to its relationship to normal plant

[1] Hartwell, B. L., and Damon, S. C., *The Value of Sodium when Potassium is Insufficient;* R. I. Agr. Exp. Sta., Bul. 177, 1919.

growth. That such a condition is more or less ideal and is seldom realized is obvious, from the fact that the various fertilizer carriers undergo more or less radical changes after being applied to the soil. The composition of the soil itself is also a disturbing factor. Nevertheless, the nearer an approach can be made to such conditions, the greater will be the economy in fertilizer practice.

Numerous persons have investigated the question as to what effect an increase of an element in the minimum may have on crop yield, and various ideas have been advanced to explain the effect. The idea of a definite law governing the increase of plant growth according as the element in the minimum is increased, was first suggested by Liebig. Wagner [1] later stated definitely that up to a certain point the increase yield was proportional to the increase in the application. This, however, evidently cannot apply except over a very limited field, since it is a matter of common observation that increased crop yield becomes lower as the lacking element is continuously supplied.

Mitscherlich [2] has formulated a law which is a logarithmic, rather than a direct, function of the increase in the element occupying the position of the minimum. Mitscherlich's law may be stated concisely as follows: the increased growth produced by a unit increase of the element in the minimum is proportional to the decrement from the maximum. In other words, the increase is proportional to the difference between the actual yield and the possible yield at which the element ceases to be a limiting factor.

Mitscherlich has proposed a definite formula for such a

[1] Wagner, H., *Beiträge zur Dungerlehre;* Landw. Jahr., Band 12, Seite 691 ff., 1883.

[2] Mitscherlich, E. A., *Das Gesetz des Minimums und das Gesetz des Abnehmen den Bodenertrages;* Landw. Jahr., Band 38, Seite 537-552, 1909.

Also, *Ein Beiträge zur Erforschung der Ausnutzung des im Minimum Vorhandenen Nährstoffes durch die Pflanze;* Landw. Jahr., Band 39, Seite 133-156, 1910.

growth curve.[1] This formula has been questioned by several investigators,[2] who have shown that a number of conditions, such as light, heat, and moisture, tend to disturb the application of such a law. The fact that crop yield is the summation of so many varying factors seems to argue in favor of no hard and fast rule regarding the increased growth due to the added increments of an element in the minimum. It is enough, in the practical utilization of fertilizers, to remember that in order to obtain the best results from fertilizers a mixture should be used that is approximately balanced so far as the effects of the nutrients are concerned, the crop as well as the chemical constitution of the soil being considered.

269. Fertilizer brands.—In an attempt to meet the demands for well-balanced fertilizers suited to various crops and soils, manufacturers have placed on the market a large number of brands of materials containing usually at least two of the important nutrient elements, and nearly always the three; the former being designated as incomplete fertilizers, while the latter are spoken of as complete. These various brands usually have a significant name,[3] which frequently implies the usefulness of the material for some special crop growing on a particular soil. Oftener, however, the brand name bears no relation either to crop or soil. The name should always be ignored in fertilizer purchase, the availability and composition being the important considerations.

[1] $\frac{dy}{dx} = (a-y)k$. Integrating, $\log (a-y) = c-kx$.

y = total yield from any number of increments.
x = amount of any particular fertilizer constituent utilized.
a = maximum yield and is a constant.
k = a constant depending on y and x, variables.

[2] Pfeiffer, Th., Blanck, E., and Flugel, M., *Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze vom Minimum;* Landw. Ver. Stat., Band 76. Seite 211-223, 1912.

Also, Mazé, P., *Recherches sue les Relations de la Plante avec les Elements Nutritifs der Sol;* Compt. Rend., Tome 154, pp. 1711-1714, 1912.

[3] Potato and Corn Fertilizer, Golden Harvest, Ureka Corn Special, Blood and Bone, Harvest King, Soil Builder and the like.

A brand of fertilizer is usually made up of a number of materials containing the important nutrient ingredients. These materials, already described, are called carriers. The making-up of a commercial fertilizer consists in mixing the various carriers together so that the required percentages of ammonia, potash, and phosphoric acid are obtained, care being taken that no detrimental reaction shall occur and that a physical condition consistent with easy distribution shall be maintained. Brands of fertilizer put out by reputable companies carry a large proportion of their nutrients in a readily available form. A fertilizer made up principally of dried blood, tankage, acid phosphate, and kainit or muriate of potash is a good example of the ordinary composition of ready mixed goods.

The various brands on the market, besides being complete or incomplete, may be designated as high-grade or low-grade as to availability, or high-grade or low-grade as to amount of plant nutrients carried. In the fertilizer trade the terms generally refer to the latter condition. A low-grade fertilizer in the latter sense is always encumbered with a large amount of inert material, called *filler,* which adds to the cost of mixing, transportation and handling. A low-grade fertilizer is generally more expensive a unit of nutrient obtained than are higher grade goods, and consequently should be avoided.

Fertilizer concerns have always found it more profitable to sell ready mixed fertilizers than to deal in the separate carriers, such as dried blood, muriate of potash, and the like. Of late years, however, it has been possible to buy the separate materials. The conditions during the World War greatly encouraged the application directly to the soil of separate carriers, especially acid phosphate, since potash was almost unobtainable and nitrogen fertilizers were very high in price. The use of phosphoric acid alone is often much more economical and rational than the use of a complete mixture, since the nitrogen removed from the soil by normal cropping and

drainage may be replaced in other and more practical ways. By maintaining the soil organic matter the natural supply of potash may in a loamy or clayey soil often be so influenced as to render a potash fertilizer unnecessary. At least there may be enough soil potash available so that the use of a commercial form will not be profitable.

270. Fertilizer inspection and control.—From the fact that so many opportunities are open for fraud either as to availability or as to the actual quantities of ingredients present, laws have been necessary for controlling the sale of fertilizers. These laws apply not only to the ready mixed goods but to the separate carriers as well. Most states have such laws, the western laws generally being superior to those in force in eastern states, where the fertilizer sale is heavier. This is because the western regulations are more recent and the legislators have had the advantage of the experience gained where fertilizers have long been used. Such laws are a protection not only to the public but to the honest fertilizer company as well, since spurious goods are kept off the market.

Certain provisions are more or less common to most fertilizer laws. In general, all fertilizers selling for a certain price or over must pay a state license fee or a tonnage tax and print the following data on the bag or on an authorized tag:

1. Number of net pounds of fertilizer to a package.
2. Name, brand, or trade-mark.
3. Name and address of manufacturer.
4. Chemical composition or guarantee.

For the enforcement of such laws the states usually provide adequate machinery. The inspection and analyses may be in the hands of the state department of agriculture, of the director of the state agricultural experiment station, of a state chemist, or under the control of any two of these. In any case, a corps of inspectors is provided, the members of which take samples of the fertilizers on the market throughout the state. These samples are analyzed in laboratories provided

for the purpose, in order to ascertain whether the mixture is up to guarantee. The expense of the inspection and control of fertilizers is usually defrayed by the license fee or the tonnage tax.

If the fertilizer falls below the guarantee,—allowing, of course, for the variation permitted by law,—the manufacturer is subject to prosecution in the state courts. A more effective check on fraudulent guarantees, however, is found in publicity. The state law usually provides for the publication each year of the guaranteed and found analyses of all brands inspected. Not only has this proved effective in preventing fraud, but it is really a great advantage to the honest manufacturer, as his guarantees receive an official sanction. The found analysis of most fertilizers is generally above the guarantee.

271. **The fertilizer guarantee.**—Every fertilizing material, whether it is a single carrier or a complete ready-to-apply mixture, must carry a guarantee. The exact form is generally determined by the state in which the fertilizer is offered for sale. The content of nitrogen is almost invariably expressed in terms of ammonia (NH_3), although the amount of total nitrogen is sometimes required in addition. The phosphorus is quoted in terms of phosphoric acid (P_2O_5). In some cases, a bone-phosphate of lime (B. P. L. or $Ca_3(PO_4)_2$) equivalent is included. The guarantee of a simple fertilizer material is easy to interpret, since the name of the material is printed on the bag or tag. When the amount of the nutrient element carried is noted, the availability and general value of the goods is immediately known. If the material is sodium nitrate at 18 per cent. ammonia, it is apparent that the fertilizer is high-grade and should give immediate and definite results when properly applied to a growing crop.

The interpretation of a complete fertilizer analysis is not as easy, however, since the names of the carriers are seldom included in the guarantees. The simplest form of guarantee

is a mere statement of the percentages of NH_3, P_2O_5 and K_2O, as, for example, a 2—8—2.[1] This, however, is too brief for a guaranteed analysis on goods exposed for sale, as it gives no idea whatsoever regarding the solubility of the materials. As might be expected, there is a wide range in the character of the guarantees required by the various states. For example, some states insist on the statement of the percentage of both nitrogen and ammonia, while others insist only on the percentage of nitrogen. Some require the soluble, the reverted, and the total phosphoric acid, while others require only the soluble and the reverted. As to potash, in some cases the soluble must be stated, while in other cases the total must be given.[2]

In general, a guarantee should show not only the amount of the various constituents but also their form or availability. The following outline analysis is excellent in this respect:

Percentage of NH_3 as nitrate.
Percentage of NH_3 as ammonia.
Percentage of NH_3 total.
Percentage of K_2O water soluble.
Percentage of K_2O as chloride.
Percentage of P_2O_5 soluble in water.
Percentage of P_2O_5 reverted.
Percentage of P_2O_5 as insoluble.

272. The buying of mixed goods.—The successful buying of mixed fertilizers on the retail market depends on two things: (1) the selection of a composition suitable to soil and crop with carriers of known value; and (2) the purchase of high-grade goods. The farmer who observes these points will at least have purchased successfully. Whether he obtains a

[1] In the South, the order is different. An 8-3-2 means 8 per cent. of P_2O_5, 3 per cent. of NH_3 and 2 per cent. of K_2O.

[2] Below is the guarantee of a complete fertilizer:

Nitrogen	4.2%
Equal to ammonia	5.0
Soluble P_2O_5	4.0
Reverted P_2O_5	2.0
Available P_2O_5	6.0
Insoluble P_2O_5	1.0
Total P_2O_5	7.0
Water soluble K_2O	3.0

profit from the use of the fertilizer depends on the interrelation of a number of factors more or less variable from season to season.

The selection of a suitable fertilizer, as to carriers and composition, entails, after the need of the crop and soil are decided, a careful study of the guarantee. Should the guarantee be such as that just cited, a large amount of information is at hand concerning the forms of the carriers and the availability of the important constituents. This knowledge, properly correlated with the probable needs of the crop and the soil, will determine whether a particular brand should be purchased or not. The real question here is not so much the actual quantities of the elements in a ton of the fertilizer, as it is their balance among themselves. The actual pounds of nitrogen, phosphoric acid, or potash applied to the acre can be governed by the rate at which the mixture is added.

The purchase of high-grade goods is the second important point to be considered. Data collected from practically every State show that the higher the grade of the fertilizer, both as to availability and as to the percentage of the constituents carried, the greater is the amount of nutrients obtained for every dollar expended. Avoiding the abnormal war prices, the following data from Vermont[1] for 1909 seem representative:

TABLE XCVIII

Mixed Fertilizer	Cost (in Cents) of One Pound of			Cents' Worth of Nutrients Received for Every Dollar Expended
	NH_3	P_2O_5	K_2O	
Low grade.....	32	7.6	8.5	50
Medium grade.....	26	6.3	7.0	60
High grade.....	23	5.7	6.3	67

[1] Hills, J. L., Jones, C. H., and Miner, H. L., *Commercial Fertilizers;* Vt. Agr. Exp. Sta., Bul. 143, pp. 147-149, 1909.

It is always true that the lower the grade of a fertilizer the higher is the proportional cost of placing the goods on the market. In other words, it costs just as much a ton to market a low-grade material as a high-grade one. This accounts for the fact that the nutrients are cheaper a pound in a high-grade mixture, and that the value received for every dollar expended is greater.

273. The purchase of unmixed fertilizers.—There has always been a tendency among fertilizer manufacturers to discourage the purchase by the farmer of the separate carriers of fertilizer nutrients. When this was possible the fertilizer manufacturer was able absolutely to control the market. By selling only mixed goods the manufacturer could not only realize a profit on the ingredients themselves but a profit on the mixing in addition. In order to escape these costs many farmers have begun the practice of buying the separate carriers, thus avoiding the extra charges. In many cases, the mixing on the farm costs nothing, as it can be done in winter when the farm work is not pressing. Home-mixing has been greatly encouraged by post-war conditions. In 1920 from ten to twenty dollars a ton was often saved on a high-grade mixture by purchasing the carriers separately.

In many instances the fertilizing materials purchased separately need not be mixed at all, thus effecting a considerable saving in time and labor. Acid phosphate is generally added separately, especially to fall wheat. Bone-meal, basic slag, and raw rock give excellent results when applied with farm manure. Sodium nitrate and ammonium sulfate give good returns as a top dressing on meadows, pastures, and small cereals, especially if phosphates have been added at some other point in the rotation. When farm manure is available, the use of acid phosphate with lime and manure in a legume rotation is generally desirable. Even where little manure is available, the application of sodium nitrate or ammonium sulfate as a top dressing for meadows, with acid phosphate in

its proper place, is feasible. The purchase of expensive ready-mixed fertilizers may thus be avoided without necessitating home-mixing.

For vegetable crops, however, especially potatoes, a complete fertilizer is generally advisable. Home-mixing is in such cases necessary. Special soils often demand a complete mixture. Muck soils generally require both potash and phosphoric acid, while sandy soils, especially if the organic matter is low, respond to a mixture carrying all three of the fertilizer elements.

As might be expected, this practice of home-mixing has met with much opposition from manufacturers. In general, it is claimed that the factory goods are more finely ground than those mixed by the farmer, and consequently the ready-mixed goods are not only more uniform but also in better physical condition. Also, the manufacturer is able to treat certain materials with acids, and thus increase their availability. While these reasons are more or less valid, good results may be expected from a fertilizer even though it may not be quite uniform, as the soil tends to equalize this deficiency. Moreover, by screening and by using a proper filler, a farmer can obtain a physical condition which will in no way interfere with the drilling of the material. While, obviously, one farmer alone cannot afford to buy small lots direct from the wholesale dealer because of the high freight charges, this objection is being met by organizations of various kinds whereby the single carriers may be purchased in carload lots and shipped directly to the association.

It is evident that by purchasing the separate carriers, a farmer is able to obtain pure high-grade material at a reasonable price. Even if the fertilizers are not home-mixed, an educational value enters. The farmer is forced to study the influence of the materials on his crops more closely and is thus placed in a position to make changes that will tend to a higher efficiency of the constituents. The chances are that he will

advantageously alter his fertilizer practice as the rotation progresses and his soil changes in fertility.

Such arguments do not always mean, however, that it pays to buy the separate materials. As a matter of fact, in many cases it does not pay, especially where only a small amount of fertilizer is needed and it is impossible to coöperate with other farmers. As a general rule, fertilizers should be bought by the method that will give the greatest value for every dollar expended, providing, of course, that the proper material is purchased. Farmers can often avail themselves of the advantage of both systems by asking for bids from various manufacturers on carload lots of mixed goods having a certain composition. The farmers in this case designate the carriers as well as the formula. All the advantages of machinery mixing may thus be gained.

274. How to mix fertilizers.[1]—The first step in the buying of the separate fertilizer carriers is to obtain quotations which should state the price a ton, the composition, and the freight rate. With this information, the most desirable carriers are selected and the amount of each is calculated.[2] If

[1] Certain materials should not be mixed, especially in large amounts. Thus lime, especially the oxide and hydroxide forms or fertilizers carrying lime in considerable amount, should not be mixed with ammonium sulfate and animal manures, since ammonia is likely to be freed. Such materials should be kept away from acid phosphate or the reversion of the latter will occur. Calcium carbonate in small amounts, however, is often mixed with fertilizers carrying acid phosphate. It is not wise to allow moist acid phosphate to lie in contact with sodium nitrate, as nitric acid may be liberated by free sulfuric acid.

[2] Below are three satisfactory mixtures:

2-12-0
- 400 pounds of tankage.
- 100 pounds of sodium nitrate.
- 1500 pounds of acid phosphate (16%P_2O_5).

2-12-2
- 320 pounds of tankage.
- 100 pounds of ammonium sulfate.
- 1500 pounds of acid phosphate (16%P_2O_5).
- 80 pounds of potassium chloride.

4-10-4
- 150 pounds of sodium nitrate.
- 100 pounds of ammonium sulfate.

the materials are to be applied separately, the rate to the acre and the number of acres must be known. If a mixture is to be made, the formula of this mixture must be decided on in addition. The pounds of the various carriers necessary to produce a given amount of a certain mixture can now be calculated. All of this is a matter of good judgement and careful arithmetic.[1]

With the separate carriers at hand, the mixing, if necessary, is quickly accomplished. All that is needed may be listed as follows: (1) a tight floor, (2) a coarse sand screen, (3) a tamper or grinder, and (4) shovels, a rake, and like tools. Since the pounds of fertilizer are quoted on each bag, weighing is unnecessary in making up a given amount of a mixture having a certain formula. Bags may be divided into half or quartered with sufficient accuracy.

The bulkiest material is spread on the floor first and leveled uniformly by raking. The remaining ingredients are then spread in thin layers above the first, in the order of their bulk. Beginning at one side, the material is next shoveled over, care being taken that the shovel reaches the bottom of the pile each time. The pile is then again leveled, and the process is repeated a sufficient number of times to insure thorough mixing. Sometimes a mixing machine may be used for this operation. For storage and general convenience, the fertilizer may be weighed into sacks of 100 to 150 pounds capacity and put in a

240 pounds of tankage.
100 pounds of dried blood.
1250 pounds of acid phosphate (16%P_2O_5).
160 pounds of muriate of potash.

[1] A 2-8-2 fertilizer is to be compounded from dried blood containing 12% NH_3, acid phosphate carrying 14% P_2O_5 and kainit containing 12% K_2O. In one ton of the mixture there should be 40 pounds of NH_3, 160 pounds of P_2O_5, and 40 pounds of K_2O.

40 ÷ .12 = 333 lbs. of dried blood.
160 ÷ .14 = 1142 lbs. of acid phosphate.
40 ÷ .12 = 333 lbs. of kainit.
192 lbs. of filler.

2000 lbs. total.

dry place until needed. Each sack should be labeled, especially if different mixtures are made.

A word of caution should be inserted here regarding the concentration of the mixture. Some farmers, in order to lessen the work of mixing and application in the field, raise the percentage of the elements exceedingly high—a condition very likely to occur when high-grade materials are used. This sometimes is bad practice, in that it may interfere with germination after the fertilizer is applied and may also injure the young plants. Also, it is likely to result in a poor physical condition, which may clog the drill, and in uneven distribution, which will bring about a lowered efficiency of the fertilizer. The use of sufficient dry finely divided filler will obviate such dangers.[1]

275. The choice of a fertilizer.—Two primary considerations must be observed in the actual utilization of fertilizers. The first of these has to do with the composition of the fertilizer and its suitability to soil and to crop. A careful study should be made not only of the percentages of ammonia, phosphoric acid, and potash but also the availability of these constituents. The second consideration in the rational use of fertilizing materials is in regard to the amounts to be applied. As much care and good judgment are necessary in handling a single carrier as a complete ready-mixed material, especially if the rotation as a whole is considered.

It is evident, due to many factors that cannot be controlled, that fertilizer formulæ for different crops on particular soils are difficult to determine. In fact, such data can never be more than merely suggestive. Further, the best quantity of a mixture to apply, even though it is perfectly balanced, is a figure that can only be approximated. Probably the largest percentage of the fertilizer waste that occurs annually can

[1] Sand, dry soil, saw dust, dry muck, and even ground limestone, if in small amounts, may be used as fillers.

be charged to this factor. Many farmers make the mistake of applying too much fertilizer. Any information along such lines, however, can only be suggestive, rather than literal, it being understood that the general formulæ suitable to various crops, and the quantities ordinarily applied, are subject to wide variations.

276. Fertilizer formulae.[1]—In the popular mind, the nutrition of a plant is considered as similar to and as easy as the proper feeding of an animal. With animals, the food is compounded with the correct balance of nutrients and if other conditions are favorable, normal results should be obtained. The nutrition of a plant is by no means as simple as the proper feeding of an animal. In the first place, the plant receives most of its nutrients from the soil and air and not from the fertilizer, since the latter usually merely supplements the nutrients already present in the soil. Again, the food for the animal remains balanced as it is utilized. In the case of plants, the fertilizer nutrients undergo great changes on addition to the soil, the soil influencing the availability of the fertilizer as well as the fertilizer influencing the soil in a great number of different ways. Moreover, the question of fertilizer residues, especially those of an acid nature, is always paramount when fertilizers are used over long periods. The proper formula for a given crop and a given soil under a probable series of weather conditions is thus more or less of a guess and will always remain so.

[1] The following example of fertilizers similarly named but carrying strikingly different guarantees are taken from Bull. 206 of the Vt. Agr. Exp. Sta.

Potatoes and Maize	Potatoes and Tobacco
4-7-8	2- 6-7
4-8-4	2- 6-4
4-8-0	2-12-0
Vegetables	**Top Dressings**
3- 7-10	7-6-5
4- 8- 4	7-6-2
5-10- 0	7-6-0

In spite of the intangible nature of the question, certain general rules seem to govern the compounding and use of fertilizers. In the first place, the ratio of the nutrients removed by the average crop bears no relation to the composition of the fertilizer usually added. This is to be expected because of the complex changes that the fertilizer undergoes in the soil and because the different nutrients influence the plant diversely.

TABLE XCIX

CONSTITUENTS	RATIO OF THE CONSTITUENTS AS THEY OCCUR IN THE AVERAGE CROP	RATIO OF THE CONSTITUENTS CARRIED BY THE AVERAGE FERTILIZER
Ammonia	4	0–2
Phosphoric acid	2	16–8
Potash	3	0–2

It is immediately noticeable that the ratios of the ammonia and potash in fertilizers are low. The ammonia ratio is low because of the ready response of plants to nitrogen and the ease with which this constituent is lost from the soil. The potash ratio is likewise small because potassium is a rather expensive constituent and it is generally better if possible to render available by suitable means that which is already in the soil than to buy it commercially. The phosphoric acid is high in comparison with the ammonia and potash because of its complex reversion in the soil and the tendency of much of it to remain unavailable for long periods due to the high absorptive power of the soil.

The following data may now be presented. These formulæ are tentative and suggestive only, being a modification and curtailment of certain analyses standardized for the use of fertilizer manufacturers in the United States.

Table C

GROUP I: FODDER AND STAPLE CROPS.

Wheat (fall)	Maize	Millet
Oats	Barley	Beans (field)
Rye (fall)	Buckwheat	Peas (field)

Soil	Without Farm Manure	With Farm Manure
Sandy soil	2-10-6	0-12-4 } or Acid
Loamy soil	2-10-4	0-12-2 } Phos.
Clayey soil	2-12-2 2-12-0	Acid Phosphate

Table CI

GROUP II: TOP DRESSINGS.

Soil	Timothy, Orchard Sod and Meadows *	Wheat, Rye and Oats for Hay (Spring Dressing) *	Pastures* and Legumes
Sandy soil	7-8-6	7-8-3	0-10-8 } or Acid Phos.
Loamy soil	7-8-3	7-8-0	0-12-4 } or Basic Slag
Clayey soil	7-8-0	7-8-0	0-12-2 } or Basic Slag

* Note.—Sodium nitrate or ammonium sulfate may be used alone as a top-dressing on all of these crops except legumes.

Table CII

GROUP III: VEGETABLES.

1. Extensively — Tomatoes, sweet corn, beets, cabbage, etc.

Sandy soil.....3-10-6
Loamy soil.....3-10-4
Clayey soil.....3-10-2 / 3-10-0

All root-crops should receive at least 2 per cent. of K_2O.

2. Intensively—Cabbage, lettuce, celery, asparagus, etc.

Sandy soil.....4-10-6
Loamy soil.....4-10-4
Clayey soil.....4-10-2

The ammonia should be reduced if farm manure is used.

3. Miscellaneous.

a. Early potatoes *	Sandy soil	7-6-5
	Loamy soil	5-8-5
	Clayey soil	4-8-4
b. Late potatoes *	Sandy soil	5-8-7
	Loamy soil	4-8-6
	Clayey soil	4-8-4
c. General trucking * on sandy soils of Atlantic seaboard		5-8-7

* Note.—Reduce ammonia if farm manure is used.

In this table of suggested formulæ, it is noticeable that wherever manure is used, the ammonia is reduced or even eliminated. Ammonia is also unnecessary on leguminous crops. With vegetables, the ammonia is usually high. Top dressings for pastures, meadows, and cereals in the spring should always carry large quantities of readily available nitrogen.

In a mixed fertilizer, the phosphoric acid is generally high, for reasons already explained. Due to the absorptive power of a clay, the mixture applied to such a soil should generally carry more phosphorus than that added to a sandy soil. Potash is usually lower in a fertilizer for clayey soils, due to the possibility of liberating potassium from the soil itself by good soil management.

277. Amounts of fertilizers to apply.—The agricultural value of a fertilizer is necessarily a variable quantity, since, in applying fertilizers, a material subject to change is placed in contact with two wide variables, the soil and the crop. Moreover, soil conditions are constantly changing, thus forcing a modification of the fertilizer applied to the same soil bearing the same crop at different times. The factors influencing the efficiency of a fertilizer application may be listed as follows: (1) seed, crop, and adaptation of crop, (2) weather conditions, (3) physical condition of the soil, including drain-

age, (4) organic content of the soil, and (5) chemical constitution of the soil and its reaction.

Although the conditions affecting fertilizer efficiency have thus been so briefly disposed of, it is evident that they are of vital importance in the economical utilization of fertilizing materials. One point of broader scope stands out particularly in this connection—the necessity of putting a soil in any given climate in the best possible condition for plant growth. This means that drainage, lime, organic matter, and tillage, in the order named, must be raised to their highest perfection in order to realize the best results from fertilizers.

Such considerations indicate that the decision as to the amount of a single carrier or of a mixed fertilizer that should be applied will be difficult and probably more indefinite than formula selection. In fact, the amount of a fertilizer applied to the acre is more vital than the actual chemical composition, as far as money returns are concerned.

With all the groups considered above, except garden and root-crops, the applications are generally relatively light, ranging from 150 to 350 pounds to an acre. Where excessive vegetative growth is required, as in silage, the rate may be increased to 500 pounds. In the top dressings of meadows or grains, the rate varies from 100 to 200 pounds an acre. Very often this dressing is sodium nitrate or ammonium sulfate alone. With garden and root-crops, the amount of fertilizer applied is very large, ranging from 800 to sometimes as high as 2000 pounds. The cropping here is intensive, and the expenditure for fertilization may be large and yet yield substantial profits.

278. The law of diminishing returns.—It must always be remembered that in fertilizer practice the very high yields obtained under fertilizer stimulation are not always the ones that give the best returns on the money invested. In other words, the law of diminishing returns is a factor in the influence of fertilization on crop yield. After a certain point

is reached, the return for each added increment of fertilizer becomes less and less. It is evident, therefore, that with an excessive application of any mixture, the returns to an increment will at last become so small that the increased crop fails entirely to pay for even the fertilizer, not to mention

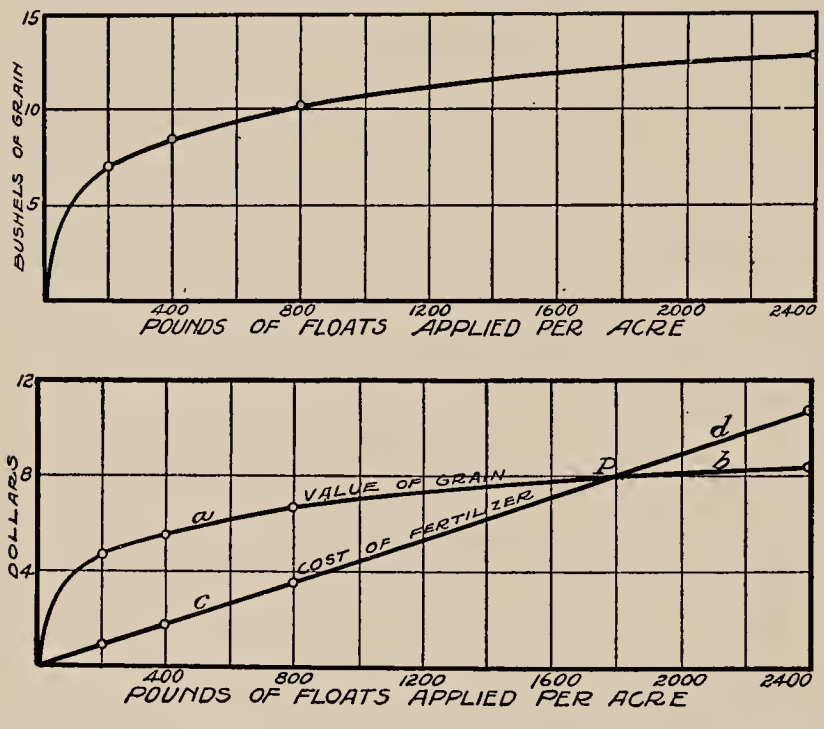


FIG. 60.—In the upper diagram the heavy line indicates the increase in the yield of maize due to graduated applications of floats. The lower diagram shows how the cost of the fertilizer approaches and finally exceeds the value of the crop as the applications increase in size.

such charges as cost of application, harvesting of increased crop, storage, and the like. The application of moderate amounts of fertilizer is to be urged for all soils until the maximum paying quantity that may be applied to any given crop is ascertained by careful experimentation. Over-fertilization probably accounts for the fact that such a large proportion of

the fertilizer sold to farmers each year not only is entirely wasted, but probably in some cases even becomes detrimental to crop yield.

The law of diminishing returns may be illustrated by data from the Cornell University Agricultural Experiment[1] Station. Floats were applied at different rates to plats receiving a uniform dressing of farm manure at the rate of 15 tons to the acre. Table CIII shows the increased yields of maize due to the treatment with the rock phosphate. Prewar prices were used in the calculations. (See Fig. 60.)

Table CIII

Pounds of Floats to the Acre	Maize (bus.)	Maize (value)	Floats (cost)	Difference
200.....	7.0	$4.62	$ .90	+$3.72
400.....	8.3	5.48	1.80	+ 3.68
800.....	10.2	6.73	3.60	+ 3.13
2400.....	12.7	8.38	10.80	— 2.42

279. Method and time of applying fertilizers.— Although considerable emphasis has been placed on the selection of the correct fertilizer formulae and on the adequate and economical amounts to use, the method of application must not be lost sight of. A fertilizer is never effective unless uniformly distributed. It should also be placed in the soil in such a position that it will stimulate the plant to the best advantage.

The distribution of the fertilizer by means of machinery is much more satisfactory than is broadcasting by hand, as the former method gives a more uniform distribution. Cereals and other crops are now usually planted with a drill or a planter provided with an attachment for dropping the fertilizer at the same time that the seed is sown, the fertilizer

[1] Lyon, T. L., *Soils and Fertilizers;* p. 216; New York, 1917.

being by this method placed under the surface of the soil. Broadcasting machines are also used, which leave the fertilizer uniformly distributed on the surface of the ground, permitting it to be harrowed in sufficiently before the seed is planted, thus preventing injury to the seed by the chemical activity of the fertilizing material.

Corn-planters with fertilizer attachments deposit the fertilizer beneath the seed, thus avoiding a possible detrimental contact. Grain-drills do not do this, and, where the amount of fertilizer used exceeds 300 or 400 pounds an acre, it is better to apply it before seeding. Grass and other small seeds should be planted only after the fertilizer has been mixed with the soil for several days. For crops to which large quantities of fertilizers are to be added, especially potatoes and garden crops, it is desirable to drop only a portion of the fertilizer with the seed, the remainder having been broadcasted by machinery and harrowed in earlier.

280. Systems of fertilization.—During the evolution of fertilizer practice since the middle of the nineteenth century, a number of systems of applying fertilizers have been advocated and in many cases actually followed. Perhaps the first plan to be suggested was the *single element system*. At that time, each crop was supposed to respond largely to one particular element. Thus, nitrogen was supposed to dominate wheat, rye, and oats; phosphoric acid, to dominate maize, turnips, and sorghum; and potash to dominate potatoes, clover, and beans. Present knowledge of plant nutrition and the balancing effects of fertilizer nutrients show this idea to be fallacious.

The supplying of *abundant minerals* as a fertilizer system had its origin from the fact that potash and phosphoric acid are relatively cheap and are rather slowly leached from the soil, while nitrogen is expensive and easily lost in this way. Such a plan, therefore, always provides plenty of potash and phosphoric acid, which are to be balanced each season with

sufficient nitrogen to give paying yields. While this system is not feasible in its entirety at the present time, the principle involved is worthy of incorporation with more economical plans.

A system based on the amount of *nutrients removed by crops* has received from time to time considerable support. According to this plan, as much plant-food material is added each year as will probably be taken out by the plant, this being determined by chemical analyses of the crop. The system not only overlooks the fact that diverse plants feed differently on the same soil, but that the same crop exhibits marked variability with change of season and change of soil. Moreover, no allowance is made for losses by leaching, which are known to equal at times the losses due to plant absorption.

In trucking or in general farming operations, one crop is often the *money crop*. Naturally its stimulation by heavy fertilization will pay better than applications to crops that bring less on the market. The general plan in this system is to allow the crops following the money crop to utilize the residuum. When this residual influence works out favorably, the system is likely to be a profitable one; but when the following crops fail to respond, the method becomes wasteful in the extreme.

281. Rational fertilizer practice.—In the selection of a system that will result in an effective utilization of fertilizers, only two of the plans described above need be considered. In any fertilizer, phosphoric acid and usually potash should always be present in amounts sufficient more than to balance the nitrogen, since the activity of nitrogen is so pronounced. Therefore, a scheme that calls for an abundance of minerals is a sound one. This, coupled with the heavy fertilization of the money crop, does not, however, constitute what might be considered a rational system, since the crops that follow may or may not be adequately supplied with nutrients.

Not only must the soil, the crop and the fertilizer formula

and amount receive careful study, but the rotation should be considered in addition. This is a fundamental principle not only with the application of commercial fertilizers but with liming and the use of farm manure as well. The careful fertilization of the rotation, with special reference to the money crop, is the only rational system that should ordinarily be employed, since it not only cares for the crop on the land but also looks to those that are to follow. The attention that must necessarily be paid to the fertility of the soil in such a system insures the establishment of a soil management which will result in an economical use of the plant nutrients, while at the same time the yields will be raised and a continuous productivity will be provided for.

CHAPTER XXIV

FARM MANURE [1]

Of all the by-products of the farm, barnyard manure is probably the most important, since it affords a means whereby the unused portion of the crop may become a part of the soil. Its use not only makes possible a return to the land of a part of the nutrients previously removed by the crop but also permits an actual gain of carbohydrate materials, the elements of which the plant obtains not from the soil but from air and water.

This country has already entered an era in which the prevention of agricultural waste is becoming necessary and a nearer approach to a self-sustaining system of soil management more and more essential. For the maintenance of fertility, a careful handling and a wise utilization of all the manure

[1] The following publications will be valuable:

Ames, J. W., and Gaither, E. W., *Barnyard Manure;* Ohio Agr. Exp. Sta., Bul. 246, June 1912.

Hart, E. B., *Getting the Most Profit from Farm Manure;* Wis. Agr. Exp. Sta., Bul. 221, June 1912.

Thorne, C. E., *Farm Manures;* New York, 1914.

Beavers, J. C., *Farm Manures;* Purdue Univ. Agr. Exp. Sta., Circ. 49, Mar. 1915.

Burdick, R. T., *Concerning Farm Manures;* Vt. Agr. Exp. Sta., Bul. 206, June 1917.

Fippin, E. O., *Farm Manure;* Cornell Reading Course for the Farm, Lesson 127, Aug. 1917.

Weaver, F. P., *Farm Manure;* Pa. State Coll., Ext. Circ. No. 67, Oct. 1917.

Brodie, D. A., *Handling Barnyard Manure in Eastern Pennsylvania;* U. S. Dept. Agr., Farmers' Bul. 978, July, 1918.

Wiancko, A. T., and Jones, S. C., *The Value of Manure on Indiana Soils;* Purdue Univ. Agr. Exp. Sta., Bul. 222, Sept. 1918.

Duley, F. L., *Handling of Farm Manure;* Mo. Agr. Exp. Sta., Bul. 166, Sept. 1919.

produced on the farm are vital. Obviously an understanding is necessary regarding the character and composition of farm manure, its fermentative and putrefactive changes, its losses in handling and storage, and above all its rational use as an amendment and a fertilizer. This need appeals not only to the wide-awake farmer but to the technical man as well, since in the use of farm manures theory and practice widely overlap.

282. Composition and general characteristics of farm manures.—The term farm manure may be employed in reference to the refuse from all animals of the farm, although, as a general rule, the bulk of the ordinary manure which ultimately finds its way back to the land is produced by cattle and horses. This arises because these animals consume the greater part of the grain and roughage on the average farm, and because the methods of handling such live-stock make it easier and more practicable to conserve their excreta. Yard manure generally refers to mixed manures. The mixing usually occurs during storage, either for convenience in handling or for the purpose of checking losses and facilitating fermentation. Thus, horse and cow manures are commonly mixed, since the too rapid putrefaction and consequent loss of ammonia in the former is checked, while at the same time a more rapid and much more complete decomposition is encouraged in the latter.

Ordinary manure consists of two original components, the solid, or dung, and the urine in about the rate of three to one. As these constituents differ greatly, not only in composition but also in physical properties, their proportions must appreciably affect the quality of the excreta and its agricultural value. Litter added for bedding or for absorptive purposes is almost always an important factor, for while it prevents losses of the soluble constituents, it may at the same time lower the value of the product for a unit amount.

While compilations of available data on the composition of

farm manures demand liberal interpretations, they afford considerable light regarding the differences to be expected between excrement from various animals.

TABLE CIV

THE COMPOSITION OF FRESH MANURE.[1]

EXCREMENT		PERCENTAGE OF			
		H_2O	NH_3	P_2O_5	K_2O
Horse	Solid, 80%	75	.66	.30	.40
	Urine, 20%	90	1.63	Trace	1.25
	Whole manure	78	.84	.25	.55
Cow	Solid, 70%	85	.48	.20	.10
	Urine, 30%	92	1.21	Trace	1.35
	Whole manure	86	.72	.15	.45
Sheep	Solid, 67%	60	.90	.50	.45
	Urine, 33%	85	1.63	.05	2.10
	Whole manure	68	1.14	.35	1.00
Swine	Solid, 60%	80	.66	.50	.40
	Urine, 40%	97	.48	.10	.45
	Whole manure	87	.60	.35	.40

Since the horse does not ruminate its food, the manure is likely to be of an open character. It is also fairly dry, as is that from sheep, the urine in these two manures making up 20 and 33 per cent., respectively, of the whole product. The complete manure from these two animals contains 78 and 68 per cent., respectively, of water—a considerable contrast to the cattle and swine excrements. Cattle and swine manures, being very wet, are rather solid and compact. The air, therefore, is likely to be excluded to a large degree and decomposition is relatively slow. They are usually spoken of as cold inert manures as compared with the dry, open, rapidly heating excrements obtained from the horse and the sheep.

[1] Van Slyke, L. L., *Fertilizers and Crops*, p. 291; New York, 1912.

In every case except that of swine, the urine is much the richer than the dung in ammonia, containing on an average more than twice as much when compared on the percentage basis. The urine is also richer in potash than the solid, averaging for the four classes of animals 1.29 per cent. as compared to 0.34 per cent. contained in the solid manure. Most of the phosphoric acid, however, is contained in the solid ex-

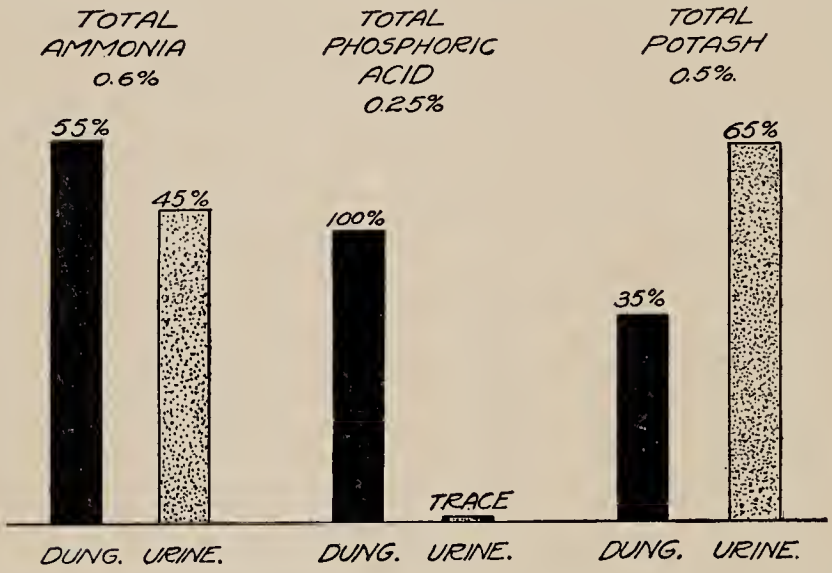


FIG. 61.—Diagram showing the distribution of ammonia, phosphoric acid and potash between the dung and urine of average farm manure.

crement, only traces being found in the urine except in the case of swine. It is, therefore, evident that the urine, pound for pound, is more valuable insofar as the nutrient elements are concerned. The advantage leans heavily toward the urine also in that the constituents therein contained are immediately available; this cannot be said of the solid manure.

283. Liquid versus solid manure.—While the urine carries more nutrients to an equal weight than the dung, it yet remains to be seen whether in the total excreta voided by an animal there are more nutrients in the urine than in the dung.

In general, more solid manure is excreted than liquid, tending to throw the advantage toward the former as a carrier of plant nutrients. The following table, adopted from Van Slyke,[1] bears on this point:

TABLE CV

DISTRIBUTION OF NUTRIENT CONSTITUENTS BETWEEN THE LIQUID AND THE SOLID OF WHOLE MANURE.

ANIMAL	PERCENTAGE OF TOTAL NH_3		PERCENTAGE OF TOTAL P_2O_5		PERCENTAGE OF TOTAL K_2O	
	SOLID	LIQUID	SOLID	LIQUID	SOLID	LIQUID
Horse	62	38	100	0	56	44
Cow	49	51	100	0	15	85
Sheep	52	48	95	5	30	70
Swine	67	33	88	12	57	43
Average	57	43	95	5	40	60
Average for horse and cow	55	45	100	0	35	65

It is seen here that a little more than one-half the ammonia, almost all the phosphoric acid, and about two-fifths of the potash, are found in the solid manure. Nevertheless, this apparent advantage of the solid manure is balanced by the ready availability of the constituents carried by the urine, giving it in total about an equal commercial and agricultural value with the solid excrement. Such figures are suggestive of the care that should be taken of the liquid manure. Its ready loss of ammonia by fermentation and putrefaction, and the ease with which all its valuable constituents may escape by leaching, should make it an object of especial regard in handling. (See Fig. 61.)

284. Poultry manure.—While poultry manure is often produced on the farm in large quantities, it is not included under the term farm manure, which, as generally used, refers

[1] Van Slyke, L. L., *Fertilizers and Crops*, p. 295; New York, 1912.

to the excrement of the larger animals. Its general composition is as below, the data being averages from Thorne.[1]

TABLE CVI

COMPOSITION OF POULTRY MANURE.

CONDITION	PERCENTAGE OF			
	H_2O	NH_3	P_2O_5	K_2O
Whole manure, fresh.....	57	1.31	.40	.50
Whole manure, air dry.....	7	2.84	.86	1.08

It is to be seen that poultry manure in the air-dry state, the condition in which it is applied, has over twice the amounts of nutrients carried by the other classes. It should be applied to the soil at at least one-half the rate commonly recommended for ordinary farm manure. Notwithstanding its ease in handling and its great value, poultry manure receives less care and attention than any other produced on the farm.

285. Farm manure—a direct and indirect fertilizer.—Farm manure, when applied to the land, ordinarily fulfills two functions which are usually not so distinctly developed in one material—that of a direct and indirect fertilizer. Mixed farm manure ready to apply to the land contains on the average .6 per cent. of ammonia, .25 per cent. of phosphoric acid and .5 per cent. potash.[2] It is obviously a low-grade fertilizer

[1] Thorne, C. E., *Farm Manures,* p. 90; New York, 1914. Also,
Storer, F. H., *Agriculture,* Vol. I, p. 613; New York, 1910.
Vorhees, E. B., *Ground Bone and Miscellaneous Samples;* N. J. Agr. Exp. Sta., Bul. 84, 1891.
Goessman, C. A., Mass. Agr. Exp. Sta., Bul. 37, 1890, and Bul. 63, 1896.

[2] See Analyses, Storer, F. H., *Agriculture,* pp. 237-248; New York, 1910.
Thorne, C. E., *Farm Manures,* pp. 89-93; New York, 1914.
Aikman, C. M., *Manure and Manuring,* pp. 279-292; Edinburgh and London, 1910.
Roberts, I. P., *The Fertility of the Land,* pp. 159-182; New York, 1904.

both as to the amounts of nutrients carried and as to their availability. Because of the large acre applications of manure commonly made, the fertilizer constituents added in manure are considerable. Ten tons of farm manure, even if only one-half its ammonia, one-sixth of its phosphoric acid and one-half of its potash were readily available, are equal in fertilizing value to 333 pounds of sodium nitrate, 52 pounds of acid phosphate, and 416 pounds of kainit. This equivalent to the addition of 801 pounds of a readily available mixture of fertilizer salts. This calculation, however, ignores an equal quantity of nutrients which remain in the soil as a residuum and may be used by succeeding crops. This residual effect of manure is generally a paying one during the period of an ordinary rotation.

Farm manure acts as an indirect fertilizer in that it adds to the soil organic matter and thus improves the physical condition of the land. While it may not increase the organic matter of the soil, because of the loss of carbon by exhalation and leaching during the period of crop growth, its use materially influences the rate of reduction. Better aëration, drainage and bacterial activity [1] of necessity result from such an addition. The influence of manure on the availability of the mineral constituents of the soil is not the least of its indirect actions. The fact that rock phosphate when mixed with manure seems to have a higher availability bespeaks a considerable solvent activity. The tendency of farm manure to alleviate toxic conditions, such as alkali and acidity, deserves attention.

286. Outstanding characteristics of farm manure.—As farm manure is essentially a fertilizer, whether it is produced on the farm or purchased outright, it is logical to contrast it with the ready-mixed materials on the market. In

[1] Conn, H. J., and Bright, J. W., *Ammonification of Manure in Soil;* Jour. Agr. Res., Vol. XVI, No. 12, pp. 313-350, March, 1919.
Fulmer, H. L., and Fred, E. B., *Nitrogen Assimulating Organisms in Manure;* Jour Bact., Vol. II, No. 4, pp. 423-434, 1917.

such a comparison, five characteristics are outstanding: (1) the moist condition of manure, (2) its low grade, (3) its unbalanced nutrient condition, (4) its variability, and (5) its rapid fermentative and putrefactive processes. These characteristics, neither present nor desirable in ordinary fertilizers, place farm manure in a class by itself as to its handling, storage, and field utilization.

Of the above points, the first three may be disposed of quickly. Average farm manure, whether fresh or well-rotted, contains from 70 to 85 per cent. water. A ton of average mixed manure when applied to the land carries but 12 pounds of ammonia, 5 pounds of phosphoric acid, and 10 pounds of potash to the ton. Approximately one-half, one-sixth, and one-half, respectively, of these constituents are readily available. Farm manure is, therefore, low-grade on two distinct counts. Moreover, its readily available nutrients approximate a ratio of about 6-1-6, a marked contrast to the 2-8-2 often given for the average ready-mixed fertilizers on the market. Obviously, manure is much too low in phosphoric acid for its content of active ammonia and potash. The variability and decomposition of farm manure will be considered separately.

287. Variability of farm manure.—The manure produced on the average farm will obviously vary in its character and composition from time to time. The factors responsible may be listed as follows: (1) class of animal, (2) age, condition, and individuality of animal, (3) food, and (4) the handling and storage which the manure receives befor it is placed on the soil.

The differences in composition due to class of animal have been adequately disposed of in previous paragraphs. In addition, it is obvious that the age and condition of any animal within a class will influence the character of the excrement produced. A young animal gaining in bone and muscle will retain large amounts of nutrients, and the manure will be correspondingly poorer in dry matter, nitrogen, lime,

phosphoric acid, and potash. A fattened animal on a maintenance ration will return almost all of the nutrient value of the original food.

Since the animal will retain only a certain quantity of the important food elements, it is only reasonable to assume that the richer the food, the richer will be the corresponding excrement. The following data from Ohio [1] obtained with western lambs substantiate this assumption:

TABLE CVII

EFFECT OF RATION ON MANURIAL COMPOSITION.

RATION	PERCENTAGE OF		
	NH_3	P_2O_5	K_2O
Corn and mix hay	1.80	.51	1.33
Corn, oil meal and hay	1.87	.53	1.22
Corn, oil meal and clover	2.03	.58	1.25

While the factors just disposed of cause some variation in farm manure, the character of the product as it goes on to the land is determined in large degree by the handling. Tight floors and proper bedding hold the liquid manure in contact with the solid and thus maintain the proportion of valuable constituents. A neglect of these two conditions means a grave loss in value. The storage of manure, when it is not taken directly to the field, always results in loss not only of organic matter, but of ammonia and minerals as well. As more than one-half of the ammonia and potash are water-soluble, serious loss is unavoidable. Such losses over-ride other causes of variation. The influence of storage is clearly shown by the following figures from Schutt [2] on mixed horse and cow

[1] Thorne, C. E., and others. *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, 1907.

[2] Schutt, M. A., *Barnyard Manure;* Canadian Dept. Agr., Centr. Exp. Farm, Bul. 31, 1898.

manure. The protected manure was stored in a bin under a shed. The exposed sample was in a similar bin but unprotected.

TABLE CVIII

LOSS OF CONSTITUENTS FROM PROTECTED AND UNPROTECTED MANURE.

CONSTITUENTS	PERCENTAGE LOSS AT END OF SIX MONTHS		PERCENTAGE LOSS AT END OF ONE YEAR	
	PROTECTED	EXPOSED	PROTECTED	EXPOSED
Loss of organic matter	58	65	60	69
Loss of NH_3	19	30	23	40
Loss of P_2O_5	0	12	4	16
Loss of K_2O	3	29	3	36

288. The fermentation and putrefaction of manure.[1]— In the process of digestion, the food of animals becomes more or less decomposed. This condition comes about partly because of the digestive process and partly from the bacterial action that takes place. Of these two influences within the animal, bacterial activities are probably of the greater importance as far as the breaking-up of the complicated foodstuffs is concerned. The fresh excrement, then, as it comes from the stable, consists of decayed or partially decayed plant materials, with a certain amount of broken-down animal tissue and mucus. This is more or less intimately mixed with litter and the whole mass is moistened with the liquid excrement carrying considerable quantities of soluble nitrogen and potash. This mass of material, ranging from the most com-

[1] Good general discussions may be found as follows: Lipman, J. G., *Bacteria in Relation to Country Life*, pp. 303-356; New York, 1911. Hall, A. D., *Manures and Fertilizers*, pp. 184-210; New York, 1921. For a technical discussion see Russell, E. J., and Richards, E. H., *The Changes Taking Place During the Storage of Farm Manure;* Jour. Agr. Sci., Vol. VIII, Part 4, pp. 495-563, Dec., 1917.

plex compounds to the most simple, is teeming with bacteria,[1] especially those that function in fermentation and putrefaction. The number very often runs into billions to a gram of excrement. In such an environment, it is little wonder that biological changes go on rapidly. These changes may be grouped for convenience of discussion under two heads—aërobic and anaërobic.

When manure is first produced, it is likely to be rather loose, and if allowed to dry at once it becomes well aërated. The first bacterial action is, therefore, likely to be rather largely aërobic in nature. Transformations are very rapid and are accompanied by considerable heat, ranging from 100° to 150° F. and sometimes higher. This action falls largely on the simple nitrogenous compounds, although the more complicated nitrogenous and non-nitrogenous constituents are by no means unaffected. Urea is particularly influenced by aërobic activities and quickly disappears from well-aërated manure.

$$CON_2H_4 + 2H_2O = NH_4)_2CO_3$$
$$NH_4)_2CO_3 = NH_3 + CO_2 + H_2O$$

Thus nitrogen may be rapidly lost from manure by allowing excessive aërobic decay and decomposition to proceed. This loss, however, is often somewhat checked by the oxidizing influence of nitrifying bacteria, especially in the outer portions of the manure pile. The evolution of carbon dioxide which goes on continuously indicates how extensively the organic matter of the manure is suffering through biological activity.

As the manure becomes compacted, especially if it is left moist, oxygen is gradually excluded from the heap and its place is taken by carbon dioxide, which is given off during the progress of any form of bacterial activity. The decay now changes from aërobic to anaërobic, it becomes slower, and

[1] Murray, T. J., *Study of the Bacteria of Fresh and Decomposing Manure;* Va. Agr. Exp. Sta., Bul. 15, Part II, 1917.

the temperature falls to as low as 80° or 90° F. New organisms may now function, although many of those active under aërobic conditions may continue to be effective. The products become changed to a considerable degree. Carbon dioxide, of course, continues to be evolved in large amounts, but instead of ammonia being formed, the nitrogenous matter is converted into the usual putrefactive products, such as indol, skatol, and the like. If sufficient reduction occurs, free nitrogen may escape.

The carbonaceous matter is resolved into numerous hydrocarbons, of which methane (CH_4) is prominent; and as a by-product of the breaking-down of the proteins, hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) are evolved. The complex nitrogenous and carbohydrate bodies are attacked with the splitting-off, not only of simpler materials, but often of those more complex. Such compounds may be listed in general as organic acids and humous bodies. They, of course, ultimately succumb to simplification.

The general changes[1] in any manure pile can readily be recapitulated. First is the aërobic action, with the escape of ammonia and carbon dioxide. Next the manure is wetted, it compacts, and the slow, deep-seated decay sets in with a simplification of some compounds, with the production of acids, and with a gradual formation of humous materials. As the manure becomes alternately wet and dry, the two general processes may follow each other in rapid succession, the anaërobic bacteria attacking the complex materials, the aërobic affecting both the complex and the simpler com-

[1] The proteid compounds, which are the most important group in farm manures, split up in the soil or compost heap into amino-acids. These amino-acids undergo deaminisation and decarboxylation. The former takes place either under aërobic or anaërobic conditions producing ammonia and a complex acid. The decarboxylation occurs only when oxygen is excluded giving either ammonia and an organic acid as in deaminisation, or carbon dioxide and a complex amine, which may be rather stable. Deaminisation and decarboxylation go on together, the former generally predominating.

pounds. Carbon dioxide is given off continuously during the process. Some gaseous nitrogen as well as ammonia is probably lost because of the rapid alternations of conditions.[1]

289. Effect of decomposition on the value of manure.— Because of the great loss of carbon dioxide and water during the decay processes, there is considerable change in bulk of the manure. Fresh excrement loses from 20 to 40 per cent. in bulk by partial rotting and 50 per cent. by becoming more thoroughly decomposed. This means that 1000 pounds of fresh manure may be reduced to 800, 600, or 500 pounds, according to the degree of change it has undergone.

It is often argued that if the manure is properly stored, this rapid loss of carbon dioxide and water will raise the percentage amounts of the fertilizer elements. The simplifying action of the anaërobic fermentation and putrefaction is an additional reason for expecting better results from well-rotted manure when it is compared, ton for ton, with the fresh material. In practice, however, the losses in handling due to leaching and fermentation are so dominant as to place well-rotted manure at a disadvantage except on sandy land or for garden and trucking purposes. At the Ohio Experiment Station,[2] yard and stall manure were compared in equal amounts in a three-year rotation of maize, oats, and hay. The yard manure was exposed for some months in the open, while the stall manure came directly from the stable. The increase due to stall manure is taken as 100 in each case. (Table CIX, p. 512.)

A change of a biological nature which sometimes takes place in loose and rather dry manure is fire-fanging. Many farmers consider this to be due to actual combustion, as the

[1] Under the alternating aërobic and anaërobic conditions found in the average manure pile, gaseous nitrogen seems to be lost in considerable amounts. This loss probably occurs through the oxidation of ammonia to nitrites or nitrates with a later reduction of the nitrogen so carried to a free state.

[2] Thorne, C. E., *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, p. 209, 1907.

TABLE CIX

COMPARATIVE YIELDS FROM YARD AND STALL MANURE.

MANURE	AVERAGE INCREASE TO THE ACRE				
	CORN, 10 YEARS		WHEAT, 10 YEARS		HAY, 6 YEARS
	GRAIN	STOVER	GRAIN	STOVER	
Stall	100	100	100	100	100
Yard	72	68	85	87	54

manure is very light in weight and has every appearance of being burned. This condition, however, is produced by fungi instead of bacteria, and the dry and dusty appearance of the manure is due to the mycelium, which penetrates in all directions and uses up the valuable constituents. Manure thus affected is of little value either as a fertilizer or as a soil amendment.

290. Evaluation of farm manure.—For purposes of comparison, experimentation, and sale, farm manures are often evaluated in a way similar to that used with commercial fertilizers. The great difficulty here lies in arriving at prices for the important constituents which are at all comparable with the value of the manure in the field. If the value of the ammonia in manure is arbitrarily placed at 15 cents a pound, phosphoric acid at 5 cents, and potash at 8 cents, certain tentative calculations may be made. While such assumptions do not establish the commercial value either of fresh or stored manure, they are of some use in comparisons and generalizations. The average manure, as it goes on the land, carries about 12 pounds of ammonia, 5 pounds of phosphoric acid, and 10 pounds of potash. Using the prices above, such manure is worth commercially about $3.00 a ton.

The *commercial* evaluation must be applied with care because of the many factors tending to vary the composition of

the excrement. Litter, particularly, will exert a great influence in this direction. Moreover, this mode of evaluation must never be confused with the much more important figure known as the *agricultural* value of a manure. The former is based on composition and assumed values of doubtful character. The latter arises from the effect of the manure on crop yield. Obviously, a rational utilization of farm manure, as with any fertilizer, should strive for the highest return to an increment applied. A very good comparison between commercial and agricultural values may be cited from the Ohio experiments [1] with manure. The manure was treated in various ways and applied to maize in a three-year rotation of maize, wheat, and hay. Twenty-six crops were grown. The commercial evaluation is taken as 100 in every case.

TABLE CX

COMMERCIAL AND AGRICULTURAL EVALUATION OF FARM MANURE.

MANURE	COMMERCIAL VALUE	AGRICULTURAL VALUE
Yard manure, untreated	100	152
Yard manure, plus floats	100	162
Yard manure, plus acid phosphate	100	222
Yard manure, plus kainit	100	192
Yard manure, plus gypsum	100	186

291. Amount of manure produced by farm animals.—A well-fed moderately worked horse will produce daily from 45 to 55 pounds of manure, of which 10 to 12 pounds is urine. A dairy cow, having a greater food capacity, will excrete from 70 to 90 pounds during the same period, of which 20 to 30 pounds is liquid. Farm animals, especially sheep and swine, vary so much in size that a thousand pound

[1] Thorne, C. E., and others, *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, pp. 206-209, 1907.

weight of animal is the only fair and logical basis of calculation.

TABLE CXI

MANURE EXCRETED BY VARIOUS FARM ANIMALS TO THE 1000 POUNDS LIVE WEIGHT.

ANIMAL	POUNDS A DAY	TONS A YEAR
Horse [1]	50	9.1
Cow [2]	70	12.7
Steer [3]	40	7.3
Swine [4]	85	15.5
Sheep [5]	34	6.2
Poultry [5]	23	4.2

It is to be noted that these figures do not include litter, which, in cases of horses and cattle, will range from 15 to 20 per cent. of the weight of the pure excrement. A working horse would be expected to produce from 10 to 11 tons of average manure a year, while a dairy cow on the same basis would produce 14 or 15 tons.

Rough calculations as to manurial production from horses and cattle may be made from the food consumed by these animals.[6] It is assumed that 50 per cent. of the dry matter of the food appears in the excrement and that the necessary bedding equals one-half of the dry matter of the excrement.

[1] Roberts, I. P., and Wing, H. H., *On the Deterioration of Farmyard Manure by Leaching and Fermentation;* Cornell Agr. Exp. Sta., Bul. 13, 1889. Also, Roberts, I. P., *The Production and Care of Farm Manure;* Cornell Agr. Exp. Sta., Bul. 27, 1891. Also, Watson, G. C., *The Production of Manure;* Cornell Agr. Exp. Sta., Bul. 56, 1893.

[2] Thorne, C. E., *Farm Manures*, p. 97; New York, 1914.

[3] Thorne, C. E., and others, *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, 1907.

[4] Watson, G. C., *The Production of Manure;* Cornell Agr. Exp. Sta., Bul. 56, 1893.

[5] Van Slyke, L. L., *Fertilizers and Crops*, p. 294; New York, 1912.

[6] Hart, E. B., and Tottingham, W. E., *General Agricultural Chemistry*, p. 125; Madison, Wis., 1913.

Average manure (bedding plus excrement) is about 75 per cent. water. This means that from 100 pounds of mixed food there results 50 pounds of manurial dry matter, 25 pounds of litter, and 225 pounds of water or 300 pounds in all. The weight of the food consumed multiplied by three should give in a rough way the weight of the fresh excrement plus its litter.

292. Loss of crop constituents in the production and handling of manure.—Any system of agriculture, whether it be grain farming, animal husbandry, or some specialized type such as trucking, must ultimately arrange for the addition of certain nutrients to replace those lost in the crop, in drainage and through biological activity. It is evident, however, that even if all of the crop constituents were returned to the soil, a constant degree of fertility would not be maintained, although the organic matter and possibly the nitrogen, if legumes were included in the rotation, might not greatly decrease. The large loss of certain nutrients in the drainage water must always be considered in any rational system of soil fertility.

Since farm manure lessens or even eliminates the need of a green-manure and at the same time offers a means of lowering the fertilizer bill, it is worth while to inquire what proportion of the nutrients contained in the crop may be returned to the soil in the resulting manure. The losses entailed are three: (1) those that occur in the handling and feeding of the crop, (2) those incurred as the food passes through the animal, and (3) those due to the handling and storage of the manure produced.

293. Losses during manurial production.—A certain amount of every crop is lost before it is finally consumed by the animal. Such loss, while important, is usually small on every farm, especially when compared to the nutrients retained by the animal. Attention is, therefore, particularly directed towards those losses sustained by the food as it un-

dergoes normal digestion. Some of the data available in this respect are quoted below:

TABLE CXII

PERCENTAGE OF ORIGINAL FOOD CONSTITUENTS RECOVERED IN FRESH MANURE.

ANIMAL	NH_3	P_2O_5	K_2O
Steers, Ohio [1]	61.0	86.8	82.4
Steers, Penn.[2]	69.4	75.1	81.2
Steers, England [3]	95.5	93.0	98.5
Milking cows, Illinois [4]	80.3	73.3	76.0
Milking cows, Penn. [5]	84.6	70.7	91.0
Milking cows, England [6]	71.8	75.0	90.0
Heifers, England [7]	77.8	78.4	86.4
Sheep, Ohio [8]	68.0	87.0	91.5

As might be expected, the data are quite variable, depending on the age, condition, individuality and class of animal, and the character of the food. As a generalization and for purposes of calculation, it may be considered that three-fourths of the ammonia, four-fifths of the phosphorus, nine-tenths of the potash, and one-half of the organic matter are recovered in the manure.[9] This means losses of about 25, 20,

[1] Thorne, C. E., *Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, p. 200, 1907.

[2] Frear, W., *Losses of Manure;* Pa. Agr. Exp. Sta., Bul. 63; Apr. 1903.

[3] Hall, A. D., *Fertilizers and Manures,* p. 180; New York, 1921.

[4] Hopkins, C. G., *Soil Fertility and Permanent Agriculture,* p. 201, Boston, 1910.

[5] Sweetser, W. S., *The Manurial Value of the Excreta of Milch Cows;* Pa. State Coll., Ann. Rep., 1899-1900, pp. 321-351.

[6] Hall, A. D., *Fertilizers and Manures,* p. 180; New York, 1921.

[7] Wood, T. B., *Losses in Making and Storing Farm Yard Manure;* Jour. Agr. Sci., Vol. II, pp. 207-215, 1907-08.

[8] Thorne, C. E., *Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, p. 202, 1907.

[9] See Hopkins, C. G., *Soil Fertility and Permanent Agriculture,* p. 206; Boston, 1910.

Also, Fippin, E. O., *Live Stock and the Maintenance of Organic*

10 and 50 per cent., respectively, for these constituents. While such losses are necessary and are usually compensated by the animal products, their magnitude must be considered in estimating the value of manure in the ordinary rotation.

294. Losses due to handling and storage.—As about one-half of the ammonia and three-fifths of the potash of average farm manure are in a soluble condition, the possibility of loss by leaching is usually great, even though the manure is not exposed to especially heavy rainfall. The loss of phosphorus is also of some consequence. In addition, decomposition, especially that of an aërobic nature, will cause a rapid waste of ammonia, one-half of that present being especially susceptible. Packing and moistening the manure will change the decay from aërobic to anaërobic, thus reducing the waste of ammonia while encouraging the simplification of the manurial constituents. Tight floors in the stables and impervious bottoms in the manure pit or under the manure pile will considerably diminish leaching losses.

It is impossible, in quoting figures for waste of manure, to separate the losses due to fermentation and putrefaction from those due to leaching. The two processes go on simultaneously, the loss from one source being dependent, to a certain extent, on the other. It is only the nitrogen, however, that may be lost by both decomposition and leaching, the minerals being wasted only through the latter avenue.

While the figures are variable (Table CXIII), it is easily seen that one-half of the ammonia and potash and one-third of the phosphoric acid are readily lost under fairly careful methods of storage. On the average farm where manure very often remains outside for several months, the losses will run much higher, easily amounting to 50 per cent. of the organic matter, 60 per cent. of the ammonia, 40 per cent. of the phos-

Matter in the Soil; Jour. Amer. Soc. Agron., Vol. 9, No. 3, pp. 97-105, Mar. 1917.

Also Armsby, H. P., and Fries, J. A., *Net Energy Values of Feeding Stuffs for Cattle;* Jour. Agr. Res., Vol. III, pp. 435-491, 1915.

phoric acid, and 65 per cent. of the potash. This means a loss of at least one-half of the nutrient constituents of the manure and considerably over one-half of the fertilizing value, since the elements wasted are those most readily available to plants. Considering the losses which the food sustains during digestion and the waste of the manure in handling and storage, it cannot be expected that more than 25 per cent. of the

TABLE CXIII

LOSSES FROM MANURE THROUGH LEACHING AND FERMENTATION.

KIND OF MANURE	HORSE [1]	HORSE [1]	HORSE [2]	COW [1]	COW [3]	STEER [4]
Days exposed....	183	183	274	183	77	91
Percentage loss of ammonia	36	60	40	41	31	30
Percentage loss of phosphoric acid	50	47	16	19	19	23
Percentage loss of potash	60	76	34	8	43	58

organic matter, 30 per cent. of the ammonia, 50 per cent. of the phosphoric acid, and 30 per cent. of the potash of the original crop will reach the land.[5] Even if leaching losses

[1] Roberts, I. P., and Wing, H. H., *On the Deterioration of Farmyard Manure by Leaching and Fermentation;* Cornell Agr. Exp. Sta., Bul. 13, 1889.

[2] Schutt, M. A., *Barnyard Manure.* Canadian Dept. Agr., Centr. Exp. Farms, Bul. 31, 1898.

[3] Thorne, C. E., *Farm Manures*, p. 146; New York, 1914.

[4] Thorne, C. E., and others, *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, 1907.

[5] Voelcker and Hall have drawn up recommendations for the compensation of the out-going English tenant for manure produced on the farm but not realized on. They suggest that he receive pay at fertilizer prices for one-half of the nitrogen, three-fourths of the phosphoric acid, and all of the potash contained in the food consumed during the last year of tenancy. For the second, third, and fourth years previous, the compensation value shall be one-half that of the year immediately preceding. Voelcker, A., and Hall, A. D., *The Valuation of Unexhausted Manures;* Jour. Roy. Agr. Soc. Eng., Vol. 63, pp. 76-114, 1902.

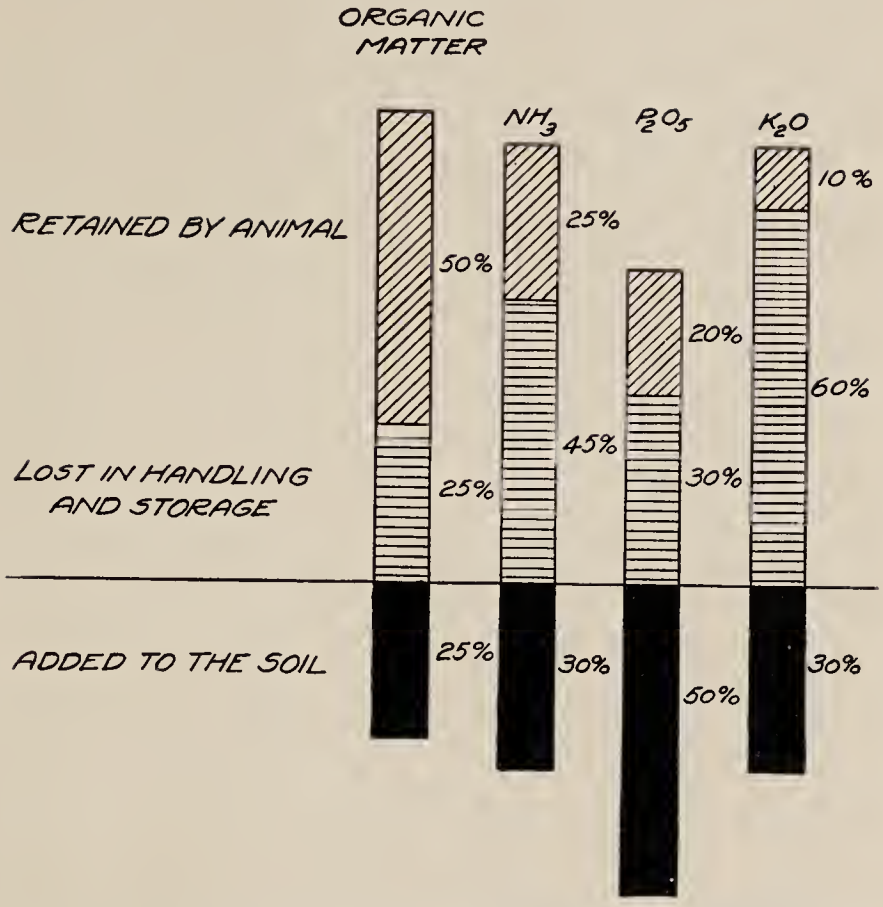


FIG. 62.—Diagram showing the proportion of the important constituents of the food retained by the animal, lost in the handling and the storage of the manure and applied to the soil under ordinary conditions.

were not important, a self-sustaining system of agriculture could not be established by the use of farm manure alone, as organic matter is the only constituent that would be added to the soil in amounts that approach the magnitude of the loss.[1]

[1] Fippin, E. O., *Live Stock and the Maintenance of Organic Matter in the Soil;* Jour. Amer. Soc. Agron., Vol. 9, No. 3, pp. 97-105, Mar. 1917.

295. Two phases of manurial practice.—A commercial fertilizer, if made properly, may be kept for long periods unimpaired and is always in a condition for instant application to the soil. The only problem confronting the farmer is the profitable application of such material. Storage is a minor factor. Farm manure, on the other hand, although a true fertilizer, presents, because of its peculiar characteristics, serious complications. As it is subject to tremendous losses by leaching, putrefaction, and fermentation, its handling and storage, if the latter becomes necessary, is as important as its rational utilization on the land. Manurial practice, therefore, is logically discussed under two headings: (1) handling and storage, and (2) utilization of the manure in the field.

296. Care of manure in the stalls.—Considerable loss to manure occurs in the stable, due to decomposition and leaching. Before the urine can be absorbed by the litter, it is likely to decay and leach away in considerable amounts. Therefore, the first care is to the bedding, which should be chosen for its absorptive properties, its cost, and its cleanliness. The following table[1] shows the approximate absorptive capacity of some common litters. (Table CXIV, page 521.)

The amount of litter to be used is determined by the character of the food. If the food is watery, the bedding should be increased. In general, the litter amounts to about one-fourth of the dry matter of the food consumed. Sheep require about a pound of bedding a head, cattle from eight to ten pounds, and horses from ten to fifteen pounds. No more litter than is necessary to keep the animal clean and to absorb the liquid manure should be used, as the excrement is

[1] Beal, W. H., *Barnyard Manure;* U. S. Dept. Agr., Farmers' Bul. 192, 1904.

Whisenand, J. W., *Water-holding Capacities of Bedding Materials for Live Stock, Amounts Required to Bed Animals, and Amounts of Manure Saved by Their Use;* Jour. Agr. Res., Vol. XIV, No. 4, pp. 187-190, July 1918.

TABLE CXIV

ABSORPTIVE POWER OF BEDDING FOR WATER.

MATERIAL	PERCENTAGE OF WATER RETAINED
Mixed shavings	124
Mixed sawdust	160
Fine pine shavings	185
Muck	200
Wheat straw	210
Oats straw	250
Peat	600
Peat moss	1300

thus diluted unnecessarily with material which often does not carry large quantities of available fertilizing ingredients.

The next care is that floors should be tight, so that the free liquid cannot drain away but will be held in contact with the absorbing materials. The preserving of manures in stalls with tight floors has been for years a common method of handling dung in England. The trampling of the animals, and the continued addition of litter as the manure accumulates, explain the reason for the success of the method. The following data, from Ohio,[1] show the relative recovery of food elements in manure produced on a cement floor and on an earth floor, respectively. The experiment was conducted with steers over a period of six months. Even with a good dirt floor, the leaching losses are considerable. (Table CXV, page 522.)

297. Hauling directly to the field.[2]—Where it is possible

[1] Thorne, C. E., *Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, p. 199, 1907.

[2] Good discussions of handling farm manure are as follows:

Hart, E. B., *Getting the Most Profit from Farm Manure;* Wis. Agr. Exp. Sta., Bul. 221, 1912.

Beal, W. H., *Barnyard Manure;* U. S. Dept. Agr., Farmers' Bul. 192, 1904.

Roberts, I. P., *The Fertility of the Land,* Chapter IX, pp. 188-213; New York, 1904.

TABLE CXV

RECOVERY OF FOOD ELEMENTS IN MANURE PRODUCED ON CEMENT FLOOR; ON EARTH FLOOR.

CONSTITUENTS	PERCENTAGE RECOVERY	
	CEMENT FLOOR	EARTH FLOOR
Ammonia	74.7	62.4
Phosphoric acid	77.5	78.9
Potash	87.8	78.4
Average	80.0	73.2

to haul directly to the field, this practice is to be advised, since opportunities for excessive losses by leaching and fermentation are thereby prevented. Manure may even be spread on frozen ground or on the top of snow, provided the land is fairly level and the snow is not too deep. This system saves time and labor, and when leaching does occur the soluble portions of the manure are carried directly into the soil. The practice of allowing the manure so spread to lie on the surface of the land all winter is sometimes questioned, especially in New England.[1] On sandy soils it may sometimes be better practice to store the manure until spring.

298. Piles outside.—Very often it is necessary to store manure outside, fully exposed to the weather. When this is the case, certain precautions must be observed. In the first place, the pile should be located on level ground far enough from any building that it receives no extra water in times of storm. The sides of the heap should be steep enough to shed water readily, while the depth of the pile should be such as to allow little leaching even after heavy storms. The earth under the manure may be slightly dished in order to prevent

[1] Brooks, W. P., *Methods of Applying Manure;* Mass. Agr. Exp. Sta., Bul. 196, Sept. 1920.

loss of excess water. If possible, the soil of the depression should be puddled, or, better, lined with cement.

The manure should be kept moist in dry weather in order to decrease aërobic action. Each addition of manure should be packed in place, the fresh on and above the older. This allows the gases from the well-rotted dung to pervade the fresher and looser portions, thus quickly establishing the anaërobic conditions so essential to economic and favorable fermentation.

Placing fresh manure in small heaps in the field to be spread later, is, in the first place, poor economy of labor. Moreover, it encourages loss by decay, while at the same time the soluble portions of the pile escape into the soil immediately underneath. There is thus a poor distribution of the essential elements of the dung, and when the manure is finally spread, an over-feeding of plants at one point and an under-feeding at another results. A low efficiency of the manure is thus realized. This method of handling manure is not to be recommended.

299. Manure pits.—Some farmers, especially if the amount of manure produced is large, find it profitable to construct manure pits of concrete. These pits are usually rectangular in shape with a shed covering. Often one or even both ends are open to facilitate the removal of the manure. In such a structure, leaching is prevented by the solid bottom while the roof allows a better control of moisture conditions. By keeping the manure carefully spread and well moistened, putrefaction may proceed with a minimum loss of nitrogen. Some European dairymen even go so far as to utilize a cistern, into which is shoveled both the liquid and the solid manure. Later when decomposition has proceeded sufficiently, the material is pumped out and applied to the land. This method is not to be advocated in this country except under special conditions, owing to the cost of handling.

300. Covered yards.—Another method of storage is by

means of a covered barnyard. Such a yard should have a more or less impervious floor. The manure is spread out in the yard and is kept thoroughly packed as well as damp by the animals. This is a common method of handling the manure in the fattening of steers in the Middle West and produces manure at a minimum loss, providing hogs are not allowed to follow the steers. The storage of manure in deep stalls, a favorite method in England, is similar to this system and has been shown to be very economical. It also affords an opportunity for the mixing of the manure from different classes of animals. The desirability of this has already been shown in the case of horse and cow excrements. The advantages of trampling, so far as the keeping qualities of manure are concerned, are clearly shown by the following figures taken from the work of Frear:[1]

TABLE CXVI

LOSS OF MANURE IN COVERED SHEDS.

CONDITION	PERCENTAGE LOSS OF		
	NH_3	K_2O	P_2O_5
Covered and tramped	5.7	5.5	8.5
Covered and untramped	34.1	19.8	14.2

Throwing manure in heaps under a shed and allowing hogs to work the mass over, is a desirable practice so far as food utilization is concerned. It interferes, however, with a proper and economical packing of the manure. The question to be decided is whether the added food value of the manure overbalances the extra losses by decomposition incurred by the rooting of the swine.

301. Increased value of protected manure.—From the previous discussion, it is evident that a well-protected and

[1] Frear, W., *Losses of Manure;* Pa. Agr. Exp. Sta., Bul. 63, 1903.

carefully preserved manure will be higher in available plant constituents than one not so handled. Moreover, the agricultural value of such manure will be higher. This is shown by actual tests from Ohio.[1] Over a period of fourteen years, in a three-years' rotation of maize, wheat, and hay, a stall manure gave a yield 38 per cent. higher than that with a yard manure.

TABLE CXVII

INCREASE YIELDS FROM YARD AND STALL MANURE.

MANURE	AVERAGE ANNUAL INCREASE TO THE ACRE		
	MAIZE 14 CROPS	WHEAT 14 CROPS	CLOVER 11 CROPS
Yard, 8 tons to the rotation	18.6 bus.	9.5 bus.	801 lbs.
Stall, 8 tons to the rotation	23.6 bus.	10.9 bus.	1395 lbs.
Increase, stall over yard manure	26.8%	14.7%	74.1%

In New Jersey, fresh manure showed a gain in crop yield 53 per cent. higher than leached manure over the three years immediately following the application. Such figures are worthy of careful consideration.

302. Application of manure.—In the application of manure to the land, the same general principles observed in the use of any fertilizer should be kept in mind. Of these, fineness of division and evenness of distribution are of prime importance. The efficiency of the manure may be raised considerably thereby. Moreover, it is generally better, since the

[1] Thorne, C. E., and others, *Plans and Summary Tables of the Experiments at the Central Farm;* Ohio Agr. Exp. Sta., Circ. 120, p. 112, 1912.

supply of manure is usually limited in diversified farming, to decrease the amounts at each spreading and cover a greater acreage. Thus, instead of adding 20 tons to the acre, 10 tons may be applied and twice the area covered. Applications could then be made oftener and a larger and quicker net return realized for each ton of manure. With manure, as with any fertilizer, the yield to the acre is not so important as the crop increase for a given increment of manure added. The influence of rate of application on increased yield to a ton of manure is shown by the Ohio [1] experiments over eighteen years in a three-year rotation of wheat, clover and potatoes, the manure being placed on the wheat.

TABLE CXVIII

INCREASED YIELD TO THE TON WHEN MANURE IS APPLIED IN DIFFERENT AMOUNTS. OHIO EXPERIMENT STATION.

RATE	WHEAT (BUS.)	CLOVER (LBS.)	POTATOES (BUS.)
4 tons to the acre.....	1.34	177	3.81
8 tons to the acre.....	.94	150	2.79
16 tons to the acre.....	.70	99	2.76

Not only is the increased efficiency from the smaller application apparent, but a greater recovery of the manurial fertility in the crops also results. The Ohio experiments show that in the first rotation after the manure is applied, a 25 to 30 per cent. higher recovery may be expected from the 8 tons treatment than from the 16 tons.

Evenness of application and fineness of division are greatly facilitated by the use of a manure-spreader. This also makes possible the uniform application of small amounts of manure,

[1] Thorne, C. E., and others, *Plans and Summary Tables of the Experiments at the Central Farm;* Ohio Agr. Exp. Sta., Circ. 120, p. 108, 1912.

even as low as 5 or 6 tons to the acre. It is impossible to spread so small an amount by hand and obtain an even distribution. Moreover, a spreader lessens the labor and more than doubles the amount of manure one man can apply a day. When any considerable quantity of manure is to be handled, a manure-spreader will pay for itself in a season or two at the most.

Whether manure should be plowed under or not depends largely on the crop on which it is used. On timothy it is spread as a top dressing. Ordinarily, however, it is plowed under. This is particularly necessary if the manure is long, coarse, and not well-rotted. It should not be turned under so deep, however, as to prevent ready decay. If manure is fine and well decomposed, it may be harrowed into the surface soil. The method employed depends on the crop, the soil, and the condition of the manure. The amount to be applied varies considerably. Eight tons to the acre would be a light dressing, 15 tons a medium dressing, and 25 tons heavy for an ordinary soil. In trucking land, however, as high as 50 or 100 tons are often used.

303. Reinforcement of manure.—The reinforcement of farm manure is designed to accomplish two things in the handling of this product: (1) checking loss due to leaching and decomposition, and (2) balancing the manure and rendering its agricultural value higher. Four chemicals may be used in this reinforcement: gypsum ($CaSO_4$), kainit (mostly K_2SO_4), acid phosphate ($CaH_4(PO_4)_2 + CaSO_4$), and floats (raw rock phosphate, $Ca_3(PO_4)_2$).

Gypsum and kainit are supposed to react with the ammonia of the manure, changing it to ammonium sulfate, a stable compound. As gypsum is rather insoluble, its action is probably slow. It may be applied either in the stable or on the manure pile, usually at the rate of 100 pounds to the ton. It has no balancing effect. Kainit is soluble and because of its caustic tendencies should not come into contact with the

feet of the animals. It must not be spread on the manure until the stock are out of the way. Since manure is unbalanced as to phosphorus, the agricultural value of kainit is slight. When applied, it is generally used at the rate of 50 pounds to the ton of manure.

Acid phosphate is partially soluble and will not only react readily with the ammonia but will tend to raise the phosphorus content to the proper point. From 40 to 80 pounds of acid phosphate are generally recommended to a ton of average farm manure. It should not be allowed to come into contact with the feet of farm animals.

Raw rock phosphate, or floats, is a very insoluble compound, and consequently reacts but slowly with the soluble constituents of manure. Carrying such a large percentage of phosphorus, it tends to balance the manure and to raise its agricultural value. It is supposed that the intimate relationship between the phosphate and the decaying manure increases the availability of the former to plants when the mixture is added to the soil. The reinforcement is usually at the rate of 75 to 100 pounds to a ton of manure.

Experimental data have shown that these various reinforcements have no particular effect on the nature, function, and number of the bacterial flora. Their conserving influence, if any, when the manure is exposed, might be in checking leaching and in preventing loss of ammonia. The following figures from Ohio experiments [1] show how slight this conserving effect is. The reinforcement was at the rate of 40 pounds to the ton. (See Table CXIX, page 529.)

It is immediately evident that kainit and gypsum do not conserve the manure, and, although acid phosphate and floats show some influence, it is slight and evidently well within the experimental error. The principal benefit from reinforcing manure, if any, must, therefore, be as a balancing agent. The

[1] Thorne, C. E., and others, *The Maintenance of Fertility;* Ohio Agr. Exp. Sta., Bul. 183, p. 206, 1907.

Table CXIX

CONSERVING EFFECT OF REINFORCING AGENTS ON MANURE EXPOSED FOR THREE MONTHS.

Treatments	Ratio Values of a Ton of Manure		Percentage Loss
	in January	in April	
No reinforcement	100	64	36
With gypsum	93	67	38
With kainit	102	66	35
With floats	128	93	27
With acid phosphate	106	75	29

figures from Ohio [1] over a period of fourteen years in a rotation of maize, wheat, and hay may be taken as evidence regarding this point. The manure treated and handled as above was added to the maize at the rate of 8 tons to the acre.

It is evident that the principal benefit of reinforcing manure lies in the balancing influence and that acid phosphate and floats are the most desirable agents. It is also evident

Table CXX

INFLUENCE OF REINFORCING ON THE EFFECTIVENESS OF MANURE.

Treatment	Average Annual Increase to the Acre			Ratio Value of Increase Per Ton of Manure
	Corn 14 Crops	Wheat 14 Crops	Hay 11 Crops	
No reinforcement	18.6 bus.	9.5 bus.	801 lbs.	100
With gypsum	23.6 bus.	11.6 bus.	916 lbs.	119
With kainit	23.7 bus.	11.3 bus.	1156 lbs.	115
With floats	25.0 bus.	12.9 bus.	1578 lbs.	138
With acid phosphate	30.6 bus.	15.1 bus.	1853 lbs.	161

[1] Thorne, C. E., and others, *Plans and Summary Tables of the Experiments at the Central Farm;* Ohio Agr. Exp. Sta., Circ. 120, p. 112, 1912.

that floats, if added in money values equal to acid phosphate, should be about as satisfactory as a reinforcing material.

304. Lime and manure.—Very often it would be a saving of labor to apply lime and manure to the soil at the same time. This can readily be done with the carbonated forms. Such lime may be mixed with the manure, either in the stable or in the pile, without any danger of detrimental results. The close union of the lime and manure may increase the effectiveness of the former and at the same time promote a better type of decomposition in the latter. If the soil is really in need of calcium, however, a separate application of lime is much better, as the amount of calcium added with the manure is never large. Caustic compounds of lime such as calcium oxide (CaO) and calcium hydroxide ($Ca(OH)_2$) must be kept from manure. These forms readily react with the ammonium carbonate coming from the urea, and cause the liberation of ammonia, which may be readily lost to the air:

$$CON_2H_4 + 2H_2O = (NH_4)_2CO_3$$
$$(NH_4)_2CO_3 + Ca(OH)_2 = CaCO_3 + 2NH_4OH$$

A stable or shed containing manure may be at once deodorized by the use of quicklime, but with the loss of much nitrogen. If the manure is to be worked into the surface soil, the caustic lime may be applied some days before and if it is in thorough contact with the soil, it will change to the carbonate before the manure is added. When the manure is plowed under, the lime is best added after the plowing and thoroughly harrowed in as the seed-bed is prepared.

305. Manure and composting.—A compost is usually made up of alternate layers of manure and some vegetable matter that is to be decayed. Layers of sod or of soil high in organic matter are often introduced. The manure supplies the decay organisms and starts biological activities. The foundation of such a compost is usually soil, and the pile is preferably capped with earth. The mass should be kept

moist in order to prevent loss of ammonia and to encourage vigorous bacterial action. Acid phosphate or raw rock phosphate and a potash fertilizer are often added, to balance up the mixture and make it a more effective fertilizer. Lime is also introduced, to react with such organic acids as may tend to interfere with proper decay. Undecayed plant tissue, such as sod, leaves, weeds, grass, sticks, or organic refuse of any kind, may thus be changed slowly to a form which will be valuable in building up the soil and in nourishing plants. Even garbage may be disposed of in such a manner.

306. Residual effects of manure.—No other fertilizer exerts such a marked residual effect as does farm manure. As it is applied in large amounts, its physical and biological influences are of necessity very great and persist for a considerable time. As only about one-half the nutrients of farm manure are readily available, the residual effect of its fertilizing elements carry over into succeeding years. Hall [1] presents the following comparative data regarding the recovery of nitrogen from various fertilizers. The crop used was mangolds. The low recovery of the nitrogen from the manure is of especial note. There is no reason to believe that the potash of the manure would be any more readily available and the phosphoric acid would certainly show a lower recovery.

TABLE CXXI

RECOVERY OF NITROGEN IN A CROP OF MANGOLDS.

	Rate to the Acre	Yield in Tons	Percentage Recovery of Nitrogen
Sodium nitrate....	550 lbs.	17.95	78.1
Ammonium salts...	400 lbs.	15.12	57.3
Rape cake.....	2000 lbs.	20.95	70.9
Farm manure.....	14 tons	17.44	31.6

[1] Hall, A. D., *Fertilizers and Manures,* p. 210; New York, 1921.

The length of time through which the effects of an application of farm manure may be detected in crop growth is very great. Hall [1] cites data from the Rothamsted Experiments in which the effects of eight yearly applications of 14 tons each were apparent forty years after the last treatment. This is an extreme case. Ordinarily, profitable increases may be obtained from manure only from two to five years after the treatment.[2] The fact remains, nevertheless, that of all fertilizers, farm manure is the most lasting and lends the most stability to the soil.

307. The place of manure in the rotation.[3]—With trucking, garden, and greenhouse crops, the applications of large amounts of manure year after year have proven advisable. As a matter of fact, manure has shown itself, especially if balanced with phosphoric acid, to be the best fertilizer for intensive operations. This is due not only to the nutrients carried by the manure, but to the large amounts of easily decomposed organic matter that are at the same time introduced. In a rotation involving the staple crops, such as maize, oats, wheat, hay, and the like, less intensive applications are advisable, not only because of a lack of manure but because the return to a ton of manure applied must be raised as high as possible. On the average farm, there is less than one ton of manure produced to an acre of arable land. Moreover, the return from manure will vary according to its place in the rotation. This has proved to be the case with commercial fertilizers and the fact is becoming more and more apparent with farm manure.

In general, meadows and pastures derive more benefit from manure, either residually or directly, than any other crop.

[1] Hall, A. D., *Fertilizers and Manures,* p. 213; New York, 1921.

[2] Voelcker, A., and Hall, A. D., *The Valuation of Unexhausted Manure Obtained by the Consumption of Foods by Stock;* London, 1903.

[3] See Thorne, C. E., *Farm Manures,* Chaps. XI and XIII, New York, 1914.

The long tests conducted by the Pennsylvania and Ohio experiment stations [1] have established this fact. The following data from Illinois [2] may be cited, comparing the response of maize and oats when manured to the increased yield of clover receiving the same treatment. (See Table CXXII, page 534.)

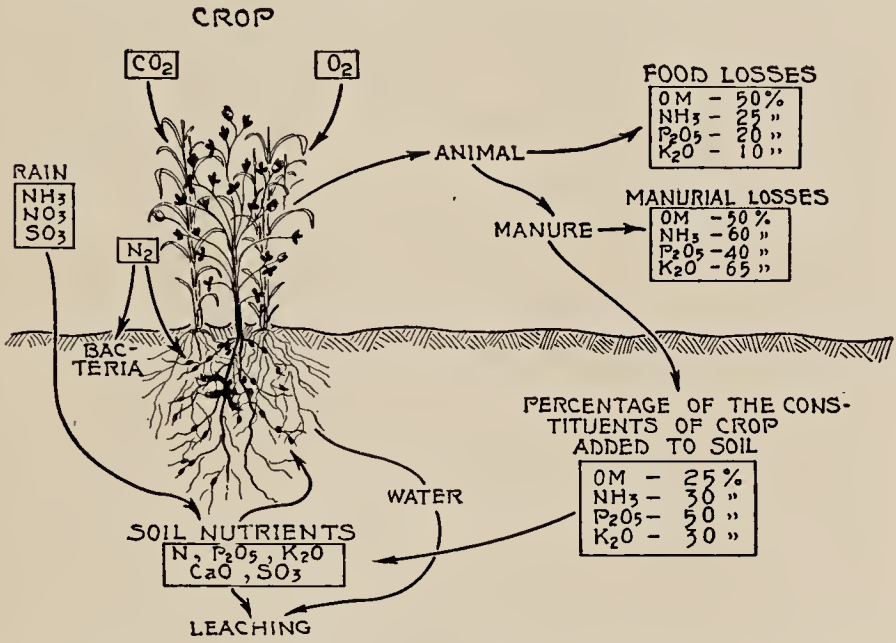


FIG. 63.—Diagram showing the proportion of the harvested crop added to the soil in farm manure under average conditions.

It is easy to see that a liberal dressing of manure on the hay and pasture will markedly increase the crop. Nevertheless, as manure is available in limited amounts on the average farm and as commercial fertilizers will give almost as good returns on hay, it is generally considered judicious, except in

[1] Hunt, T. F., *General Fertilizer Experiments;* Ann. Rep. Penn. Agr. Exp. Sta., 1907-1908, pp. 68-93.

Thorne, C. E., and others, *Plans and Summary Tables of the Experiments at the Central Farm;* Ohio Agr. Exp. Sta., Circ. 120, pp. 101-105, 1912.

[2] Hopkins, C. G., *Thirty Years of Crop Rotation in Illinois;* Ill. Agr. Exp. Sta., Bul. 125, p. 337, 1908.

TABLE CXXII

INFLUENCE OF MANURE ON MAIZE, OATS, AND CLOVER.

TREATMENT	AVERAGE PERCENTAGE INCREASE		RATIO VALUE OF INCREASE	
	MAIZE AND OATS	CLOVER	MAIZE AND OATS	CLOVER
Manure alone..	11	92	100	134
Manure, lime and phosphate	30	141	162	206

certain cases, to reserve most of the manure for other crops. The top dressing of meadows is, however, always an allowable practice, especially on new seeding or on hay land that is soon to be plowed for maize.

As a food producer, maize has no close rival. Where the climate is favorable, a 75-bushel crop of maize is as easily secured as 40 bushels of wheat or 300 bushels of potatoes to the acre. Moreover, the maize stover may be made more valuable as roughage than the straw of oats, wheat, or rye. The maize plant must have, however, for its successful growth plenty of available nitrogen. In addition, its response to abundant organic matter indicates the utilization of certain organic compounds. These considerations argue for the use of most of the farm manure on the maize when this crop is important, especially if the supply of manure is limited. Again the maize crop is ready for the manure in the spring and is generally grown on land where the excreta may be distributed during the previous winter and fall.

Potatoes are a spring crop and where they are prominent in the rotation may receive liberal applications of manure. If potatoes are the money crop, this should by all means be the practice. Oats, because of the tendency to lodge, generally follow maize or potatoes as a residual feeder, receiving, if necessary, a dressing of commercial fertilizer. If manure is

used on fall wheat, a great loss of manurial value is incurred, due to the necessity of storage during the summer months. Moreover, commercial fertilizers high in phosphorus are so convenient and effective on wheat that the use of manure on this crop is becoming rather uncommon, although manure may be used to advantage as a fall and winter dressing, since it not only stimulates the wheat but is of great value to the new seeding as well. Where cotton and tobacco are the staple crops, they should receive at least a part of the manure produced. The value of manure in orchards should not be overlooked, especially on sandy soils. The up-keep of organic matter, the conservation of moisture, and the nutrients supplied are as important here as in any phase of soil management.

308. **Resume.**—Barnyard manure, from the standpoint of soil fertility, is the most valuable by-product of the farm. A careful farmer will, therefore, attempt to utilize it in the most economical way. The handling of manure in such a manner that only a minimum waste occurs from the time the manure is voided until it has reached the land is not an easy problem. Manure is so susceptible to the loss of valuable ingredients, both by leaching and by decay, that careful methods must be employed. Tight floors in the stable and covered sheds or manure pits are always advisable. Hauling immediately to the field is the wisest procedure, yet even with the best of care more than 50 per cent. of the fertilizing value is usually lost. The problem of rational manurial utilization is not solved, however, by careful handling and storage alone. Manure must be applied in such a condition, in such amounts and at such a point in the rotation as to realize a reasonable return for every increment applied. The reinforcement of farm manure with phosphoric acid is by no means an unimportant feature. In fact, all of the principles which are observed in the profitable utilization of commercial fertilizers should be adhered to in the use of farm manures.

A permanent system of agriculture evidently cannot be established by merely returning all the manure possible to the land, as approximately only 25 per cent. of the organic matter, 30 per cent. of the ammonia, 50 per cent. of the phosphoric acid, and 30 per cent. of the potash of the food consumed on the farm ever reach the land in the manure. Nevertheless, it is certainly worth the while of a farmer to use some care in handling this product and some thought as to its rational utilization in the field. Even if the manure should aid only in the up-keep of organic matter, the effort would be worth while. Reasonable care in the handling of farm manure will save this country thousands of pounds of manurial fertility which are now utterly lost and at the same time increase by thousands of dollars the food production.

CHAPTER XXV

GREEN-MANURES[1]

From time immemorial the turning-under of a green-crop to supply organic matter to the soil has been a common agricultural practice. Records show that the use of beans, vetches, and lupines for such a purpose was well understood by the Romans, who probably borrowed the practice from nations of greater originality. The art was lost to a great extent during the Middle Ages, but was revived again as the modern era was approached. At the present time, green-manuring is considered a part of a well-established system of soil management, and is given a place, when possible, in every rational plan for permanent soil improvement.

309. Importance of green-manures.—The plowing under of some succulent rapid-growing crop, such as oats, rye, or clover, tends to bring about three desirable soil conditions; additional organic matter, a betterment of the physical condition of the soil, and a rise in the nitrogen content of the land, if the crop is an inoculated legume. If conditions are

[1] Penny, C. L., *Clover Crops as Green Manures;* Del. Agr. Exp. Sta., Bul. 60, 1903.

Storer, F. H., *Agriculture,* pp. 137-175; New York, 1910.

Lipman, J. G., *Bacteria in Relation to Country Life,* Chapter XXIV, pp. 237-263; New York, 1911.

Piper, C. V., *Leguminous Crops for Green Manuring;* U. S. Dept. Agr., Farmers' Bul. 278, 1907.

Spillman, W. J., *Renovation of Worn-out Soils;* U. S. Dept. Agr., Farmers' Bul. 245, 1906.

Pieters, A. J., *Green Manuring: A Review of the American Experiment Station Literature;* Jour. Amer. Soc. Agron., Vol. 9, No. 2, pp. 62-82, Feb. 1917; Vol. 9, No. 3, pp. 109-126, Mar. 1917; Vol. 9, No. 4, pp. 162-190, Apr. 1917.

favorable, an increase in crop production should result. Where there is a shortage of farm manure, the practice becomes of special importance since roots and crop residues are usually insufficient to maintain the organic content of the soil. Even where manure is available, a green-manuring crop now and then in the rotation does much towards sustaining normal production.

The effects of turning under green plants are both direct and indirect—direct as to the influence on the succeeding crop, and indirect as to the soil so treated. In the first place, certain ingredients are actually added to the soil by such a procedure. The carbon, oxygen, and hydrogen of plants come largely from the air and water, and the plowing-under of a crop, therefore, increases the store of such constituents in the soil. The compounds that result from crop decay increase the absorptive power of the soil, and promote aëration, drainage, and granulation—conditions that are extremely important in successful plant growth. If the crop turned under is a legume and the nodule organisms are active, the store of soil nitrogen is markedly augmented, a point of extreme importance in fertilizer practice.

Green-manures may function also as cover-crops, insofar as they take up the extremely soluble plant nutrients and prevent them from being lost in the drainage water. The nitrates of the soil are of particular importance in this regard as they are very soluble and are absorbed only slightly by the soil complexes. Besides this, green-manures, especially those with long roots, tend to carry nutrients upward from the subsoil and when the crop is turned under this material is deposited within the root zone. Again, the added organic material acts as a food for soil organisms, and tends to stimulate biological changes to a marked degree. This biological action is especially important in the production of carbon dioxide, ammonia, nitrates, and organic compounds of various kinds, which are necessary in plant nutrition.

310. Gain of constituents by green-manuring.—In an average crop of green-manure, from five to ten tons of material are turned under. Of this, from one to two tons are dry matter, and from four to eight tons water. Of this dry matter, a great proportion is carbon, hydrogen, and oxygen. It might seem at first thought that such an addition is pure gain as far as carbon and carbonaceous matter are concerned. Such is not the case. Large amounts of carbon are lost continuously in drainage, to say nothing of that removed by crops or that which is respired by the soil as carbon dioxide. It has already been shown, from results obtained with the Cornell lysimeters, that a heavy soil will yearly lose over 250 pounds of carbon, in drainage alone (see par. 220). This is approximately equivalent to a 2-ton application of green-manure. Although the loss of carbonaceous material is considerable, even during the period that the green-manuring crop is being grown, nevertheless the practice offers a rapid as well as a natural means of increasing the soil organic matter.

The mineral parts of the turned-under crop came from the soil originally and they are merely turned back to it again and represent no gain. As they return, however, they are in intimate union with organic materials, and are thus readily available as the decay processes go on. Indeed they are probably more readily available than they previously were, when the green-manuring crop acquired them.

The amount of nitrogen added to a soil if the green-manure is a legume [1] is an uncertain quantity. Much depends on the virulence of the organisms occupying the nodules. These bac-

[1] Smith, C. D., and Robinson, F. W., *Influence of Nodules on the Roots upon the Composition of Soybean and Cowpea;* Mich. Agr. Exp. Sta., Bul. 224, 1905.

Hopkins, C. G., *Alfalfa on Illinois Soil;* Ill. Agr. Exp. Sta., Bul. 76, 1902.

Hopkins, C. G., *Nitrogen Bacteria and Legumes;* Ill. Agr. Exp. Sta., Bul. 94, 1904.

Shutt, F. T., *The Nitrogen Enrichment of Soils through the Growth of Legumes;* Canadian Dept. Agr., Rept. Centr. Exp. Farms, 1905, pp. 127-132.

teria are in turn much influenced by plant and soil conditions, such as amount of organic matter, presence of nitrates, acidity and the like. Hopkins [1] estimates that about one-third of the nitrogen in a normal innoculated legume comes from the soil and two-thirds from the air. He also considers that one-third of the nitrogen exists in the roots.

Both of these assumptions are questionable and at best tentative. The amount of nitrogen fixed by legume organisms is extremely variable, probably more so than that assimilated by the azotobacter and allied groups. Again the percentage of the nitrogen held in the roots of legumes is by no means the same for all species. The amount varies within the species with age, degree of maturity and, season. The Delaware investigations [2] show that the proportion of the total nitrogen of the plant occurring in the roots may be as low as 6 per cent. in case of cowpeas and as high in the roots of alfalfa as 42 per cent. A range from 6 to 28 per cent. of the total nitrogen of crimson clover was noted in the roots under different conditions.

According to Hopkins, the nitrogen found in the tops of legumes will be a rough measure of the nitrogen fixed by the nodule organisms. When the crop is turned under, this will represent the gain to the soil. If the preceding assumption is correct, red clover turned under would actually add about 50 pounds of nitrogen for every ton of air-dry substance utilized, alfalfa about 50, cowpeas 43, and soybeans 53 pounds. These figures, even though they may be far from correct, at least give some idea of the possible addition of nitrogen by green-manuring practices, and show how the soil may be enriched by such management. As in the case of farm manures, the indirect effects of such a procedure on the physical and bacteriological properties of the soil may over-ride the direct

[1] Hopkins, C. G., *Soil Fertility and Permanent Agriculture*, p. 223; Boston, 1910.

[2] Penny, C. L., *The Growth of Crimson Clover;* Del. Agr. Exp. Sta., Bul. 67, 1905.

influences, lessening the advantage that legumes as green-manures are supposed to have over non-legumes, due to their ability to use atmospheric nitrogen.

311. Green-manures as cover-crops.—When green-manures are seeded in the late summer or early fall, they function as cover-crops and may have rather important influences aside from their effects when turned under. Their greatest influence seems to be on the nitrate content of the soil. Nitrification is usually checked,[1] a disappearance of nitrates generally following. This reduction in the amount of nitrates probably occurs because of a retardation of nitrification accompanied by a stimulation of biological utilization of the nitrates. Such an effect is important in conserving the soil nitrogen and is of particular value in orchards,[2] as it hastens the maturity of the new growth. At Cornell University, green-manures were seeded in July and plowed under in the following spring. Nitrate determinations were made on the soil in July and in October. The figures are five-year averages. (See Table CXXIII, page 542.)

312. The decay of green-manure.—When a green-crop is turned under, the process of its decay is the same as that of any plant tissue that becomes a part of the soil body. The organisms that are active are those common to the soil, together with such bacteria as are carried into the soil on the turned-under crop. The decomposition that results is probably both aërobic and anaërobic in nature, carbon dioxide being given off continuously. When proper decay has occurred, end products should result which can be utilized as nutrients.

[1] Wright, R. C., *The Influence of Certain Organic Materials upon the Transformation of Soil Nitrogen;* Amer. Soc. Agron., Vol. 7, pp. 193-208, 1915.

Martin, T. L., *The Decomposition of Green Manures at Different Stages of Growth;* Thesis for degree of Doctor of Philosophy, Cornell University, 1919.

[2] Lyon, T. L., *The Formation of Nitrates in Soil Under Grass;* Proc. West. N. Y. Hort. Soc., pp. 82-87, Jan., 1915.

Lyon, T. L., *Relation of Certain Cover Crops to the Formation of Nitrates in Soil;* Proc West. N. Y. Hort. Soc., pp. 32-34, Jan., 1917.

TABLE CXXIII

EFFECT OF VARIOUS CROPS ON THE NITRATE NITROGEN OF THE SOIL DURING OCTOBER, 1916-1920.[1]

GREEN-MANURING CROP	NITRATES IN THE SOIL IN OCTOBER. RYE TAKEN AS 100	PERCENTAGE REDUCTION OF NITRATES IN OCTOBER COMPARED WITH JULY
Rye	100	37
Oats	73	44
Vetch	73	57
Peas	83	10
Rye and vetch	74	58
Rye and peas	75	58
Sod	6	0

The intermediate compounds that are formed should yield an organic matter carrying a black pigment, should readily split up into simple compounds, and should be in general beneficial, both directly and indirectly, to plant growth. Plenty of moisture is essential when green-manures are decaying, not only to hasten the transformation itself but that the normal soil processes may not be interrupted by a lack of water. The caution with which green-manures must be utilized in semi-arid regions arises because of the drying influences of rapid decay and the danger of filling the soil with undecomposed plant residues. Even in humid regions, green-manures may be detrimental if dry weather sets in before a major portion of the decay processes is completed.

As plant tissue decays in the soil, there seem to be two general groups of forces at work which produce three distinct stages of organic destruction.[2] In the first stage, humus pro-

[1] Unpublished data. Dept. Soils. Cornell University.

[2] Martin, T. L., *The Decomposition of Green-Manures at Different Stages of Growth;* Thesis for degree of Doctor of Philosophy, Cornell University, 1919.

duction is dominant and the amount of the humous materials increases. In the second stage, humus production and humus destruction are more or less balanced, while in the third stage humus destruction is in the ascendant. The amount of humus is on the decrease in the latter stage. The length of these stages will vary with the season, with soil conditions,[1] and with the character of the crop turned under. Obviously, the influence of decomposing green-manure on the chemical and biological activities of the soil will vary as the decay cycle progresses. In general, over one-half of the organic matter of the average green-manure disappears during the first nine months after application.

313. Influence of decaying green-manure.—In the first stage of decay, which should be a rapid one, many complex compounds are generated along with carbon dioxide and other simple products. The complex materials, which result partly from protein decomposition and partly from the breaking down of easily attacked carbohydrates, may be harmful to ordinary crops. Germinating seeds and young plants are especially susceptible, and detrimental influences are sometimes noticed immediately after the turning under of a green-manure. Fred[2] found that the germination of oily seeds, such as cotton and soybean, was much reduced. Starchy seeds, such as maize, oats, and wheat, were little affected. The germination of flax, hemp, mustard, and clover was somewhat reduced. An actual contact of the seed with the decaying material was usually necessary for serious damage. The detrimental influence always occurred during the first two or three weeks after the green-crop was turned under. Obviously the more succulent the crop, the shorter will this period be.

[1] Russell, E. J., and Appleyard, A., *The Influence of Soil Conditions on the Decomposition of Organic Matter in the Soil;* Jour. Agr. Sci., Vol. VIII, Part 3, pp. 385-417, 1917.

[2] Fred, E. B., *Relation of Green Manure to the Failure of Certain Seedlings;* Jour. Agr. Res., Vol. V, No. 25, pp. 1161-1176, Mar., 1916.

Not only do the products of the first stage of decay influence the crop growing on the soil, but they affect the biological activities as well.[1] Nitrification in particular seems to be influenced, as nitrates do not begin to appear until the process of humification is well advanced. Nitrification, however, is probably not entirely suppressed as it is possible for soil organisms to use up the nitrates as rapidly as they are formed.

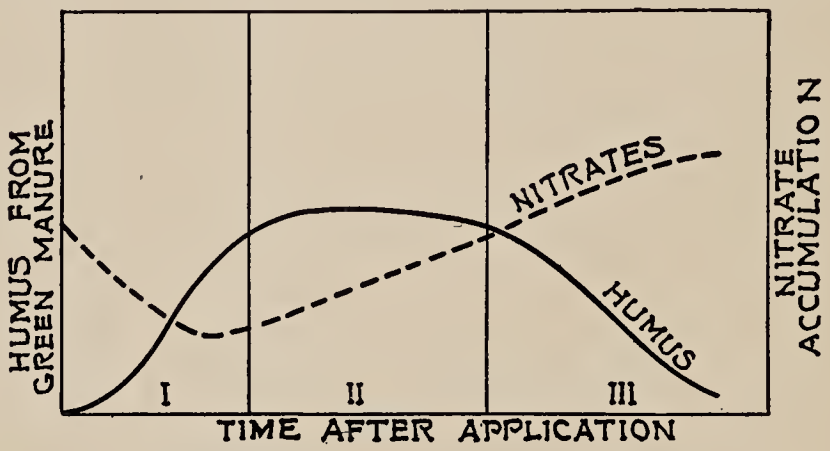


FIG. 64.—Diagram illustrating the three stages in the decay of a green-manure. I, humus production dominant; II, a balance between humus production and destruction; III, humus destruction dominant. A depression in nitrate accumulation generally occurs in stage I followed by an increase. (After Martin.)

As the humus destruction gradually dominates over humus production, the end products of the decay become prominent. The complex proteid decomposition is practically completed and cellulose destruction is slowly progressing. Of the simple nutritive products, the nitrates are of particular importance. In fact, they have been chosen by a number of in-

[1] Briscoe, C. F., and Harned, H. H., *Bacterial Effects of Green Manures;* Miss. Agr. Exp. Sta., Bul. 168, Jan. 1915.
Hutchinson, H. B., *The Influence of Plant Residues on Nitrification and on Losses of Nitrates in Soil;* Jour. Agr. Sci., Vol. IX, Part 1, pp. 92-111, Aug. 1918.

vestigators [1] as a measure of humification, since a favorable environment for nitrification probably does not occur until the more rapid decomposition processes are completed. In general, the more rapid the decay of the green-manure, the sooner will nitrification be active again.

Besides affecting the bacterial activity of the soil, the decaying green-crop influences the solubility of the soil minerals. Jensen [2] found that the addition of 3 per cent. of green-manure raised the solubility of lime and phosphoric acid 30 to 100 per cent. This was over and above the mineral constituents which came directly from the decomposing green-crop. Magnesium and iron were also markedly influenced.

314. Crops suitable for green-manures.—An ideal green-manuring crop should possess three characteristics: rapid growth, abundant and succulent tops, and the ability to grow well on poor soils. The more rapid the growth, the greater the chance of economically using such a crop as a means of soil improvement. The higher the moisture content of the crop, the more rapid the decay and the more quickly are benefits obtained. As the need of organic matter is especially urgent on poor land, a hardy crop has great advantages.

The crops that may be utilized as green-manures are usually

[1] Hutchinson, C. M., and Milligan, S., *Green-Manuring Experiments, 1912 and 1913.* India Agr. Res. Inst. Bul. 40, Pusa, India, 1914.

Maynard, L. A., *The Decomposition of Sweet Clover as a Green-Manure under Greenhouse Conditions;* Cornell Agr. Exp. Sta., Bul. No. 394, 1917.

Martin, T. L., *The Decomposition of Green-Manures at Different Stages of Growth;* Thesis for degree of Doctor of Philosophy, Cornell University, 1919.

[2] Jensen, C. A., *Effect of Decomposing Organic Matter on the Solubility of Certain Inorganic Constituents of the Soil;* Jour. Agr. Res., Vol. IX, No. 8, pp. 253-268, May 1917.

See also, Snyder, H., *Humus as a Factor in Soil Fertility;* Minn. Agr. Exp. Sta., Bul. 41, 1895; and *Production of Humus from Manures;* Minn. Agr. Exp. Sta., Bul. 53, 1897.

Hopkins, C. G., and Aumer, J. P., *Potassium from the Soil;* Ill. Agr. Exp. Sta., Bul. 182, 1915.

Hopkins, C. G., and Whiting, A. L., *Soil Bacteriology and Phosphates;* Ill. Agr. Exp. Sta., Bul. 190, 1916.

grouped under two heads, legumes and non-legumes. Some of the common green-manures are as follows:

LEGUMES		NON-LEGUMES
Annual	Biennial	
Cowpea	Red clover	Rye
Soybean	White clover	Oats
Peanut	Alsike clover	Mustard
Vetch	Alfalfa	Mangels
Canada field pea	Sweet clover	Rape
Velvet bean		Buckwheat
Crimson clover		
Hairy vetch		

When other conditions are equal, it is of course always better to choose a leguminous green-manure in preference to a non-leguminous one, because of the nitrogen that may be added to the soil. However, it is so often difficult to obtain a catch of some of the legumes that it is poor management to turn the stand under until after a number of years. Again, the seed of many legumes is very expensive, almost prohibiting their use as green-manures. Among the legumes most commonly grown as green-manures, cowpeas, soybeans, and peanuts may be named. Many of the other legumes do not so fit into the common rotations as to be turned under conveniently as a green-manure.

For the reasons already cited, the non-legumes have, in many cases, proved the more popular and economic as green-manures. Rye and oats are much used because of their rapid, abundant, and succulent growth and because they may be accommodated to almost any rotation. They are hardy and will start in almost any kind of a seed-bed. They are thus extremely valuable on poor soils. Often the value of such a green-manure as oats is greatly increased by sowing peas with it. The advantages of a legume and a non-legume are thus combined.

It has already been shown that the nitrate production in a

soil may be used as a rough measure of the rate of decay of green-manures. Admitting such a criterion, certain data from Cornell University become particularly interesting. In a five-year continuous test, green-manuring crops were seeded in July and plowed under in the early part of the succeeding May. The nitrate content of the soil was determined at a number of times during the spring, summer, and fall. A decrease in nitrates always occurred in the autumn, while an increase began soon after the crops were turned under in the spring. In the following table the rye crop is taken as 100 in both October and July:

TABLE CXXIV

RELATIVE INFLUENCE OF GREEN-MANURES ON THE ACCUMULATION OF SOIL NITRATES.[1]

GREEN-MANURE	NITRATES IN JULY, SOIL FALLOW SINCE MAY 1. RYE TAKEN AS 100	NITRATES IN OCT., SOIL UNDER CROP SINCE JULY. RYE TAKEN AS 100
Rye	100	100
Oats	78	73
Vetch	120	73
Peas	99	83
Rye and vetch	136	74
Rye and peas	102	75

It is immediately apparent that the succulent rye and vetch that survive the winter give better results, as far as nitrate production is concerned, than the dry and dead oats and peas. This shows clearly the value of succulence and the necessity of turning under a crop partially matured.[2] The advantage of the legumes over the non-legumes is not hard to explain.

[1] Unpublished data. Dept. Soils, Cornell University.

[2] Martin, T. L., *The Decomposition of Green Manures at Different Stages of Growth;* Thesis for the Degree of Doctor of Philosophy, Cornell University, 1919.

The combination of rye and vetch, both of course in a succulent condition, seems especially efficacious. Sod as a green-manure always appears more or less at a disadvantage.

315. The use of green-manures.—The indiscriminate use of green-manures is of course never to be advised, as the soil may be injured thereby and the normal rotation much interfered with. When soils are poor in nitrogen and organic matter, they are very often in poor tilth. This is true whether the texture of the soil be fine or coarse. The turning-under of green-crops must be judicious, however, in order that the soil may not be clogged with undecayed matter. Once or twice in a rotation is usually enough for such treatments. Proper drainage must always be provided. In regions where the rainfall is scanty, great caution must be observed in the handling of green-manures. The available moisture that should go to the succeeding crop may be used in the process of decay, and the soil left light and open, due to an excess of undecomposed plant tissue. In western United States, it is still a question whether green-manures have any advantage over summer fallowing.

It is generally best to turn under green-crops when their succulence is near the maximum and yet at a time when abundant tops have been produced. This occurs at about the half mature stage. A large quantity of water is carried into the soil when the crop is at this stage, and the draft on the original soil-moisture is less. Again, the succulence encourages a rapid and more or less complete decay, with the maximum production of humus and other products. The plowing should be done, if possible, at a season when a plentiful supply of rain occurs. The effectiveness of the manuring is thereby much enhanced. At Cornell University various green-manures were seeded in the summer and plowed under that fall or the next spring. The experiment was continuous for three years, the nitrates being determined in the soil each year in April and in June. The results are as given on the next page.

TABLE CXXV

INFLUENCE OF THE TIME OF TURNING-UNDER OF GREEN-MANURES ON THE NITRATE ACCUMULATION IN THE SOIL.[1]

CROP	PARTS PER MILLION OF NITRATES	
	IN APRIL JUST BEFORE THE SPRING PLOWING	IN JUNE, SOIL FALLOWED SINCE PLOWING
Rye, fall plowed	58	57
Rye, spring plowed	53	67
Oats, fall plowed	61	42
Oats, spring plowed	36	50
Vetch, fall plowed	79	45
Vetch, spring plowed	41	67
Average, fall plowed	66	48
Average, spring plowed	43	61

It is apparent that the decay of the green-manuring crop is hastened by fall plowing, as the nitrates in every case are higher in April on land so handled. In June, however, the nitrate accumulation has passed its highest point in the fall-plowed soil, leaving the spring-plowed plats, where the decay was initiated later, in the ascendancy. The table also shows the advantage that a legume has over a non-legume in causing nitrate accumulation. Oats fall-plowed appear about on an equality with rye. Spring plowing, since the oats are then dry and dead, gives the rye a marked advantage. All of the points above noted have a very practical field application.

In turning under green-manures, the furrow slice should not be thrown over flat, since the green-crop is then deposited as a continuous layer between the surface soil and the subsoil. Capillary movement is thus impeded until a more or

[1] Unpublished data. Dept. Soils, Cornell University.

less complete delay has occurred, and the succeeding crop may suffer from lack of moisture. The furrow ordinarily should be turned only partly over, and thrown against and on its neighbor. The green-manure is then distributed evenly from the surface downward to the bottom of the furrow. When decomposition occurs, the resulting materials are evenly mixed with the whole furrow slice. Moreover, this method of plowing does not interfere with the capillary movements of water, and in actual practice is a great aid in drainage and aëration.

316. Green-manure and lime.—The decay of organic matter in the soil is always accompanied by the production of organic acids of various kinds. The greater the succulence of the material, the more rapid is the accumulation of such products. In spite of this, however, the effect of a green-manure is to decrease the acidity rather than increase [1] it and later greatly to stimulate nitrification even if the soil originally was quite acid. The decrease in lime requirement may be due to the liberation of mineral constituents from the decaying organic matter and to the effect of the decomposition on the inorganic constituents of the soil.

The ultimate influence of green-manure on acidity is somewhat in doubt. The bulk of the evidence available seems to indicate that decaying organic matter, if it has any effect, ultimately tends to decrease rather than increase the lime requirement of the soil.[2] Nevertheless, plenty of active calcium should be in the soil, since it promotes the decay of the plant tissue added and seems to control to a certain extent the presence of toxic materials. Lime may be added to the green-manure seeding and be turned under with that crop. The

[1] White, J. W., *Soil Acidity as Influenced by Green Manures;* Jour. Agr. Res., Vol. XIII, No. 3, pp. 171-197, April, 1918.

[2] Hill, H. H., *A Comparison of Methods for Determining Soil Acidity and a Study of the Effects of Green Manures on Soil Acidity;* Va. Poly. Inst., Tech. Bul. 19, April 1919.

Ames, J. W., and Schollenberger, C. J., *Liming and Lime Requirement of Soils;* Ohio Agr. Exp. Sta., Bul. 306, pp. 381-383, Dec. 1916.

amendment would thus be in very close contact with the decaying vegetable tissue. Ordinarily, however, the application of lime at some point in the rotation is sufficient.

Lime, besides its capacity to alleviate toxic residues, tends to hasten organic decay.[1] This is a very important function as the first stage of decomposition, during which soil and plant activities may under certain conditions be detrimentally affected, is markedly shortened. Such a promotion is indicated in a green-manuring experiment at Cornell University. The green-manures were seeded in the fall under two treatments, limed and unlimed. The parts per million of nitrates in the soil are given for two dates on the year succeeding, the green-manures having been plowed under either in the fall or early spring. The data are averages of three years.

TABLE CXXVI

INFLUENCE OF LIME ON THE NITRATE ACCUMULATION IN A SOIL RECEIVING VARIOUS GREEN-MANURES.[2]

Crop and Treatment	Parts Per Million of Nitrates	
	April	June
Rye, no lime	66	53
Rye, limed	45	71
Oats, no lime	53	43
Oats, limed	45	50
Vetch, no lime	77	52
Vetch, limed	43	63
Average, no lime	65	49
Average, limed	44	61

[1] Lemmermann, O., *et al., Untersuchung über die zerzetzung der Kohlenstoff Verbindungen Verscheidcner Organischen Substanzen im Boden Spezielle unter dem einfluss der Kalk;* Landw. Jahrb., Bd. 41, S. 216-257, 1911.

[2] Unpublished data. Dept. Soils, Cornell University.

The effect of lime on nitrification is very noticeable in June. In April the no-lime plats are higher in accumulated nitrates, due to the lesser growth of the green-manuring crop.

317. Practical utilization of green-manures.—Green-manures seem to have their greatest value where a permanent instead of a rotation pasture is used, where a long cycle rotation of grain is practiced, or where little or no manure is available. The experimental data bearing on the use of green-manures seems to indicate that such a practice is productive of larger crop yields. The following data from Nappan, Nova Scotia, is from one of the more reliable and conclusive experiments. A catch-crop of clover in the grain was turned under for grain the following year. The figures are for 1905, the third year of the test.

TABLE CXXVII

YIELD OF WHEAT, OATS AND BARLEY IN BUSHELS TO THE ACRE ON THE NAPPAN FARM IN 1905 ON PLATS CROPPED CONTINUOUSLY TO GRAIN.[1]

TREATMENT	WHEAT	OATS	BARLEY
No green-manure.....	34.3	41.2	32.7
Clover catch-crop.....	40.0	55.3	37.9

The use of a green-manure is often determined by the character of the rotation. Very often it is somewhat of a problem as to when, in an ordinary rotation, a green-manure may be introduced so that it may fit in well with the crops. In a rotation of maize or potatoes, oats, wheat, and two years of hay, a green-manure might be introduced after the corn or potatoes. This would not be a very good practice, however, as a cultivated crop usually should follow a green-manure in order to facilitate decomposition and decay. In such a rotation, the plowing-under of the hay stubble is really a form

[1] Ottawa Exp. Farms Rept., 1905, p. 284.

of green-manuring, there being a considerable accumulation of stubble and aftermath on the soil. When a rotation of this kind is used, it is better either to supply organic matter in other ways, or to alter or break the rotation in such a manner as to admit of a more advantageous use of green-crops.

Where trucking crops are raised and no very definite rotatice is adhered to, green-manuring is easier. It is especially facilitated when cover-crops are grown, as in orchards. Soiling operations also favor the easy and profitable use of green-manures. In general, it may be said that the organic matter obtained from such a source should be supplemented by farm-yard manures where possible. A better balanced and richer soil organic matter is more likely to result.

CHAPTER XXVI

THE MAINTENANCE OF SOIL FERTILITY [1]

The maintenance of a profitable and continuous soil productivity is an intricate problem, since many variable factors are involved. Weather conditions, moisture relations, soil organic matter and tilth, plant diseases, soil reaction, and available nutrients are only a few of the influences that function continuously throughout the growing season. No scheme of soil management and crop production is perfect, even though it is fairly profitable. Except in special cases, every system is open to improvement and modification as soil and plant knowledge increases.

The sources of knowledge regarding the profitable growing of plants are numerous. Much data have arisen from experience and observation, much are empirical, while some are confessedly conjectural. In spite of the large amount of scientific information available regarding the soil and its plant relationships, practical experience has contributed more towards a profitable and continuous soil productivity. Soil survey classification and mapping have contributed something. Field tests, both practical and technical, have added to such information, while laboratory and greenhouse experiments, although often arbitrary and artificial, are by no means unimportant. These latter contributions, however, always need practical confirmation under typical field conditions over a period of years.

318. Loss of plant nutrients from the soil.—A consideration of the principles governing the rational management

[1] Fertility is here used in the sense of continuous productivity.

of a soil is obviously impossible unless some knowledge is at hand regarding the losses and additions which a soil sustains in the course of a definite rotation. Fortunately, some fairly reliable data have already been presented regarding the removal of soil constituents under controlled conditions. The Cornell lysimeter tanks, bearing a rotation of maize, oats, wheat, and two years of hay, offer very satisfactory information (paragraphs 95 and 163). The losses covering a ten-year period are expressed in pounds to the acre a year. The soil is a Dunkirk silty clay loam.

While such figures are probably open to considerable error and obviously would not apply with any degree of accuracy to a light soil, they indicate in a general way the magnitude and order of the losses that may be expected from such a soil under the conditions specified.

TABLE CXXVIII

LOSSES FROM A DUNKIRK SILTY CLAY LOAM SOIL EXPRESSED IN POUNDS TO THE ACRE A YEAR OVER A TEN-YEAR PERIOD. ROTATION: MAIZE, OATS, WHEAT AND TWO YEARS HAY. CORNELL LYSIMETER TANKS.

SOURCE OF LOSS	N	P_2O_5	K_2O	CaO	SO_3
Drainage (par. 163)....	7.3	trace	68.7	345.9	108.5
Cropping (par. 163)....	70.5	43.5	105.4	24.3	41.0
Atmosphere (pars. 220 and 233)[1].....	?	——	——	——	——
Total.....	77.8	43.5	174.1	370.2	149.5

The organic carbon in this soil over the ten-year period was reduced at the rate of approximately 1 per cent. a year.[2] This is equivalent to a reduction in organic matter of about 1200

[1] The largest loss of carbon is probably to the atmosphere as carbon dioxide. The other avenue of loss is in the drainage water.

[2] Lipman and Blair report a reduction of organic carbon of .74 per cent. a year over a period of ten years on Sassafrass loam in New

pounds each year to the acre-four feet. It is evident, therefore, that the losses sustained by the average soil fall most heavily on the organic constituents, a condition often ignored in practical soil management. The removal of calcium oxide is also very large, being equivalent to a loss of 661 pounds of calcium carbonate an acre a year. Although losses of sulfur trioxide and phosphoric acid are smaller than that of the potash, they are far more important, since there is very commonly one hundred times more potash in a soil than of the other two constituents combined. The magnitude of the loss of a soil constituent is never a safe measure of its importance. The removal of nitrogen is equivalent to over 500 pounds of commercial sodium nitrate and consequently is also a loss of no small consideration.

319. Additions of nutrients to the soil.—The figures presented above are based on reliable experimental data. Unfortunately the information regarding the additions which normally occur to a soil under any particular rotation are by no means so exact. Certain assumptions and estimates, often of questionable validity, must be admitted in order that a complete survey may be possible. Table CXXIX sets forth the additions which the Dunkirk clay loam of the Cornell lysimeters may reasonably be expected to receive each year when cropped to a five-year rotation of maize, oats, wheat, and two years hay. The data are expressed in pounds to the acre a year. (See Table CXXIX, page 557.)

The additions listed above are not the only avenues open for important acquisitions. The crops removed may be fed to animals and the manure returned to the land. Moreover, the utilization of a green-manure is also possible. Below will be found the additions that may reasonably be expected from the

Jersey. The rotation was maize, oats, wheat, and two years hay. No lime was added.

Lipman, J. G., and Blair, A. W., *The Lime Factor in Permanent Soil Improvement. I. Rotations Without Legumes;* Soil Sci., Vol. IX, No. 2, p. 87, 1921.

Table CXXIX

ESTIMATED ADDITIONS THAT MIGHT OCCUR TO A SOIL UNDER A ROTATION OF MAIZE, OATS, WHEAT, AND TWO YEARS HAY. EXPRESSED IN POUNDS TO THE ACRE A YEAR.

Source of Addition	N	P_2O_5	K_2O	CaO	SO_3
Rain-water (pars. 236 and 264)	12.5	—	—	—	65.0
Free fixation by soil organisms (par. 238)	25.0	—	—	—	—
Crop-roots and residues [1]	—	—	—	—	—
Total	37.5	—	—	—	65.0

use of farm manure and a green-manure on the soil in question. The green-manure is leguminous and is applied once during the five-year rotation.

Table CXXX

FURTHER ADDITICNS THAT MIGHT BE MADE TO THE FIVE-YEAR ROTATION ON DUNKIRK SILTY CLAY LOAM, EXPRESSED IN POUNDS TO THE ACRE A YEAR.

Additions	N	P_2O_5	K_2O	CaO	SO_3	Organic Matter
Farm manure [2]	21.1	21.7	31.6	7.3	12.4	1000
Leguminous green-manure [3]	20.0	—	—	—	—	600
Total	41.1	21.7	31.6	7.3	12.4	1600

[1] Important because of the additions of organic matter that occurs thereby.

[2] It is estimated that of the crops removed and fed or used as bedding, only 30 per cent. of the N, K_2O, CaO and SO_3, 50 per cent. of the P_2O_5 and 25 per cent. of the organic matter reach the soil as farm manure (par. 294). The crops removed carried about 4000 pounds of organic matter to the acre.

[3] The green-manure is estimated as 4000 pounds of air-dry matter carrying 100 pounds of nitrogen, which is considered as fixed from the air. This should yield 3000 pounds of soil organic matter.

320. The balance sheet.—For convenience of comparison, the data previously presented are drawn together in a single table and presented below as pounds to the acre annually. These figures are considered as relating to the Dunkirk silty clay loam carrying a five-year rotation of maize, oats, wheat, and two years hay. It must always be remembered that such data are specifically applicable to only one soil. Nevertheless the practical deductions that may be drawn are of wider scope.

TABLE CXXXI

SUMMARY TABLE OF LOSSES AND ADDITIONS THAT MIGHT OCCUR TO DUNKIRK SILTY CLAY LOAM UNDER A FIVE-YEAR ROTATION. EXPRESSED IN POUNDS TO AN ACRE A YEAR.

CONDITIONS	N	P_2O_5	K_2O	CaO	SO_3	ORGANIC MATTER
Reductions when farm manure and green manure are not used[1]	40.3	43.5	174.1	370.2	84.5	1200
Additions from farm manure	21.1	21.7	31.6	7.3	12.4	1000
Additions from farm manure and green-manure	41.1	21.7	31.6	7.3	12.4	1600
Additions using green-manure	20.0	—	—	—	—	600

It is immediately apparent that when farm manure and green-crops are not utilized, a notable decrease occurs in every constituent cited. Such a system of soil management must reduce the productivity of the soil very quickly and certainly is not a rational scheme of soil and crop adjustment. Nevertheless, it is the condition under which much of the arable land is producing crops today.

When farm manure is utilized, even allowing for a large

[1] Obtained by subtracting the natural additions from the normal losses.

waste in its production and handling, the organic matter is almost maintained and the loss of nitrogen is met to some extent. Under such a system, the addition of nitrogen and of mineral constituents is a problem, although some attention should be paid to the soil organic matter. Liming will be necessary ultimately if not immediately, while the addition of phosphoric acid obviously will some day be profitable. If acid phosphate is utilized at a normal rate, the sulfur losses that occur should be very nearly counterbalanced. Potash, especially as the soil under consideration is a clay loam, will no doubt be available for a long period if the organic matter is adequately maintained.

The use of a green-manure once in the rotation in addition to the farm manure will adequately care for the soil organic matter and reduce the nitrogen problem to a minor position.

When animal products are relatively high in price and crop values are low, stock farming will be advisable and a system whereby considerable farm manure will be available may be followed. It has already been indicated that under such conditions the organic matter, and to a lesser degree the nitrogen content of the soil, may adequately be maintained especially if a green-manure is used once in the rotation. Where grain farming is necessary, reliance must be placed almost wholly on green-manures for the upkeep of the soil organic matter, especial care being given to the full utilization of crop residues. According to the data presented in Table CXXXI, such a system, as far as the nitrogen and organic matter are concerned, could be made about as satisfactory as where farm manure is available and has the possibility and advantage of considerable expansion. Grain farming makes necessary, however, a more intensive and careful use of mineral constituents. Liming and commercial fertilizers will, therefore, figure somewhat more prominently in grain-growing than where dairying or stock-raising are practiced.

321. The maintenance of soil fertility.[1]—The practical management of a soil, whereby profitable crops may be grown without materially reducing the fertility of the land rests on five fundamental principles. The basic factors are: (1) drainage, (2) tillage, (3) organic matter, (4) lime, and (5) fertilizers. Obviously, the removal of excess water depends on adequate drainage, while aëration and all of the activities that attend it rests both on drainage and tillage. The upkeep of the soil organic matter by the use of crop roots and residues, by farm manure, and by the turning under of green-crops has already been emphasized as fundamental to continuous productivity.

These factors are by no means the whole program of rational soil management. Artificial additions must be made. Of these lime is of vital importance. Calcium and magnesium are lost from the soil in such large amounts that outside sources must be drawn on. Every arable soil will ultimately come to the point where liming will be profitable. Finally, the judicious use of commercial fertilizers must receive attention. The addition of phosphoric acid will probably be the first fertilizer element to be considered seriously, especially in general farming. Under special conditions of soil and crop, nitrogen and potash will also be a part of the program. The adaptation of crops in suitable rotation to climate and soil, with adequate attention to the factors emphasized above, are the prime essentials of a paying system of permanent soil productivity.

[1] Hartwell, B. L., and Damon, S. C., *Six Years' Experience in Improving a Light Unproductive Soil;* Jour. Amer. Soc. Agron., Vol. 13, No. 1, pp. 37-41, 1921.

Lipman, J. G., and Blair, A. W., *The Lime Factor in Permanent Soil Improvement. I. Rotations without Legumes. II. Rotations with Legumes;* Soil Sci., Vol. IX, No. 2, pp. 83-114, 1921.

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